Networks for applied infectious disease epidemiology

WINQ program on complex and quantum systems

Lucille Calmon – May 1, 2024

Infectious diseases
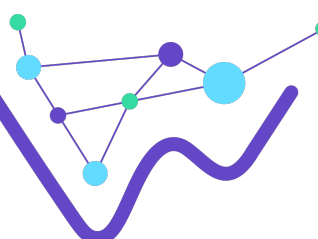

The Guardian, 17/03/2020

Nature, 08/04/2024

NEWS EXPLAINER | 08 April 2024

Bird flu outbreak in US cows: why scientists are concerned

A virus that has killed hundreds of millions of birds has now infected cattle in six US states, but the threat to humans is currently low.

By Max Kozlov & Smriti Mallapaty

The New York Times

As Monkeypox Spreads, U.S. Declares a Health Emergency

The designation will free up emergency funds and lift some bureaucratic hurdles, but many experts fear containment may no longer be possible.

The New York Times, 04/08/2022
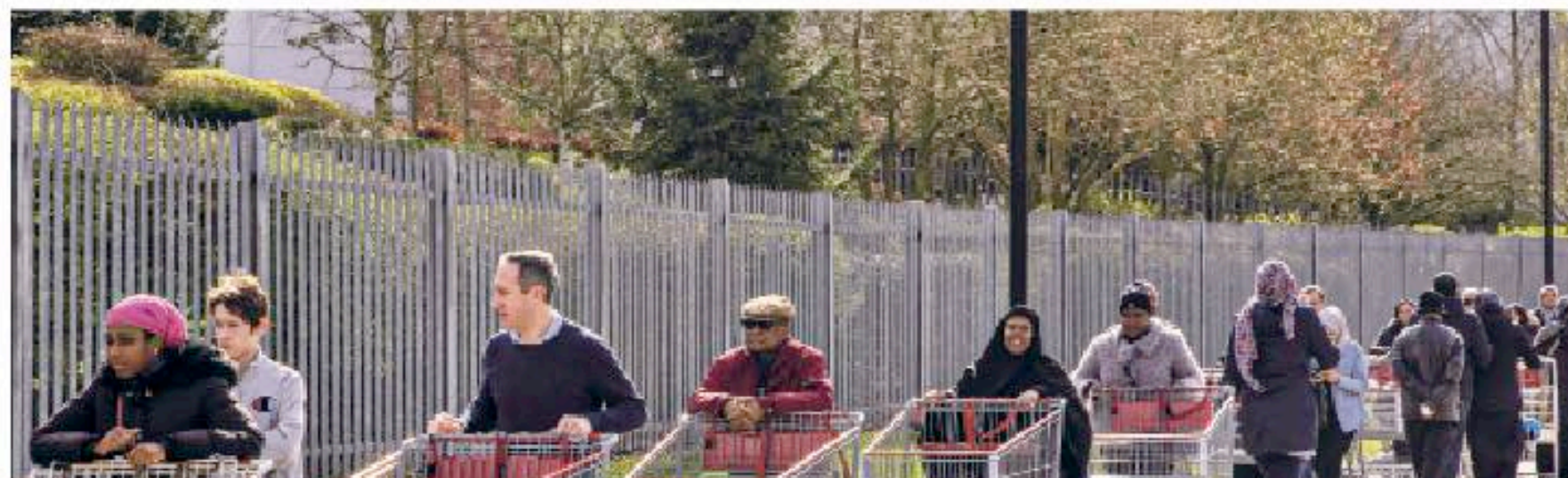
Modelling infectious disease dynamics

- Risk evaluation, forecasting/nowcasting

- Comparison of intervention protocols

- Mechanisms behind observed dynamics

- Behaviour ↔ dynamics

Colosi, et al (2022) *The Lancet Infectious Diseases*
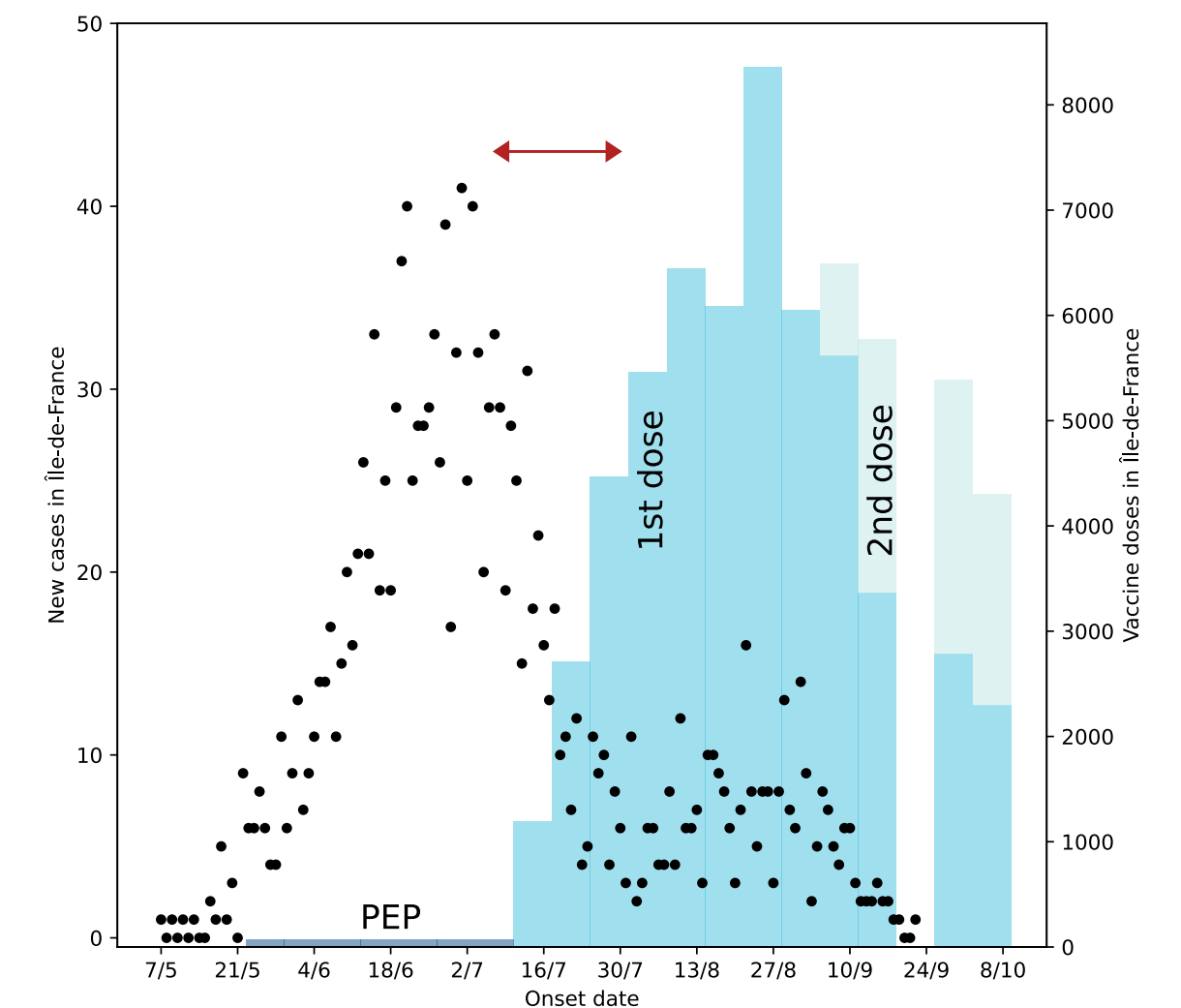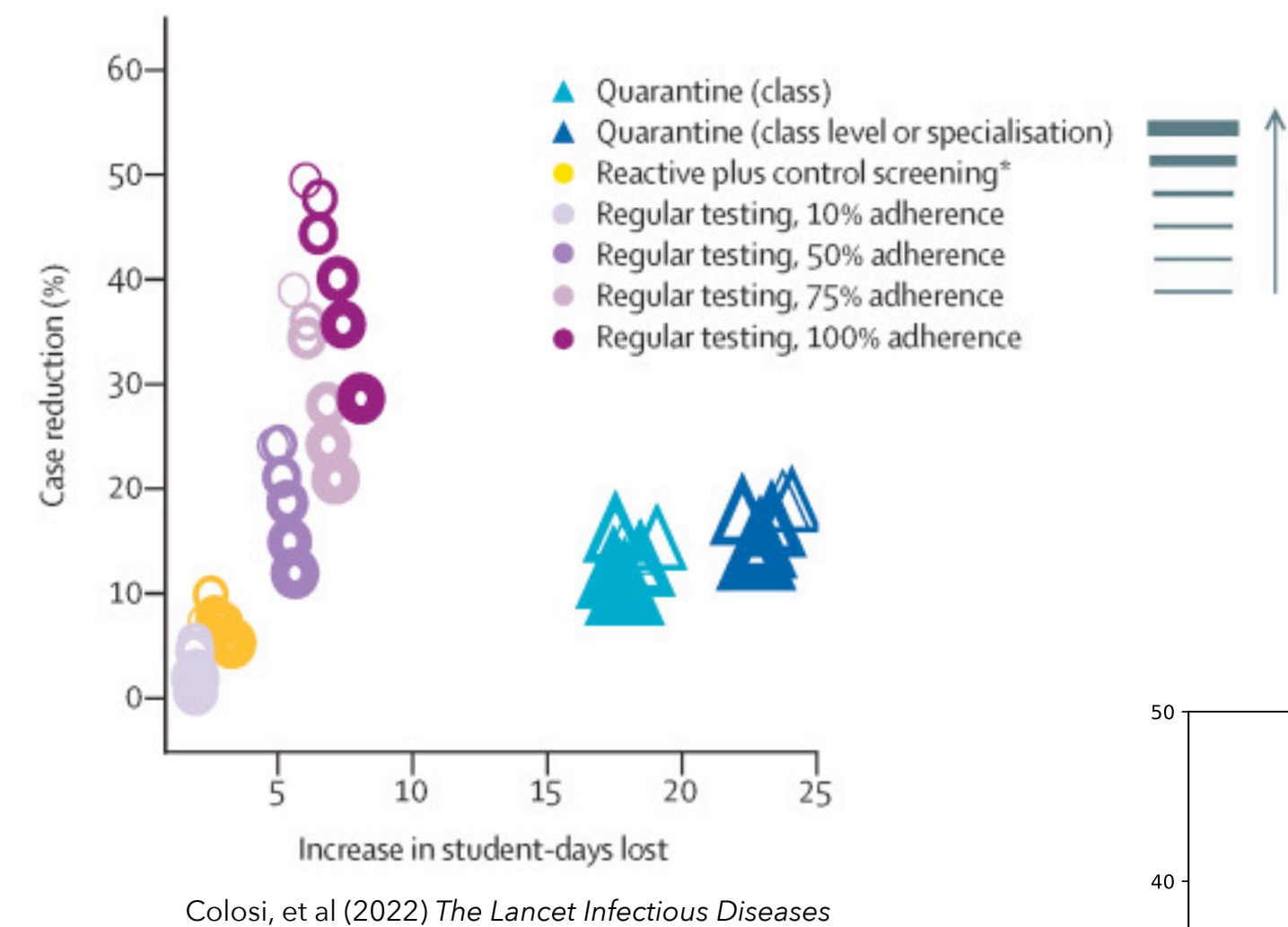
Maniscalco et al. (2024) *in prep*

Mixing in different details

Colizza et al (2007) *Comptes Rendus Biologies*
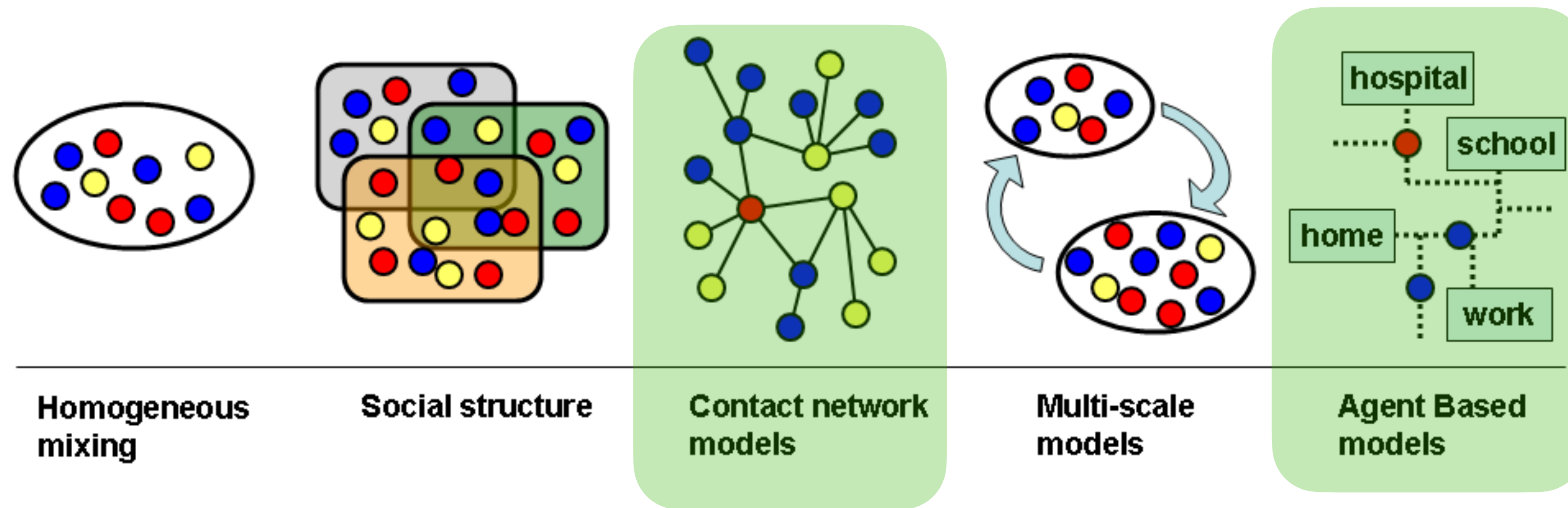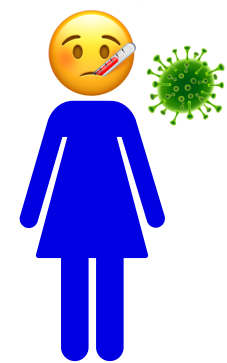
➡️ **How can we construct contact networks to inform models**

Outline

- Building blocks of a contact network model

- How can we measure contacts ?

- Tools to leverage on measured contacts to inform models

- Why ? The example of the Swiss pooling tests protocol

Modelling infectious disease dynamics

Clinical progression

Progression modelled with a compartmental model (e.g. SIR).
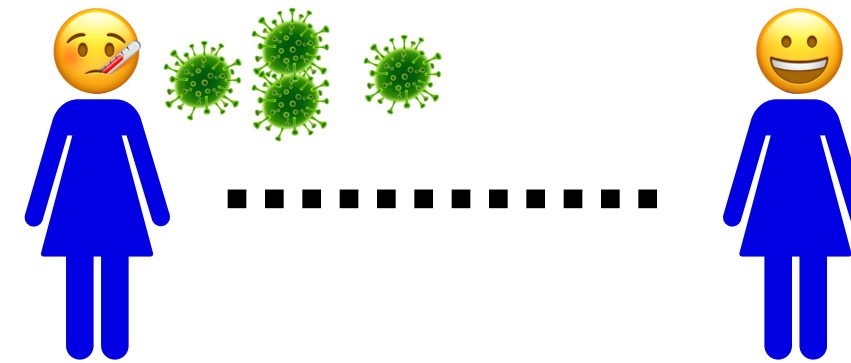
Transmission

Transmissibility of the pathogen, contact characteristics
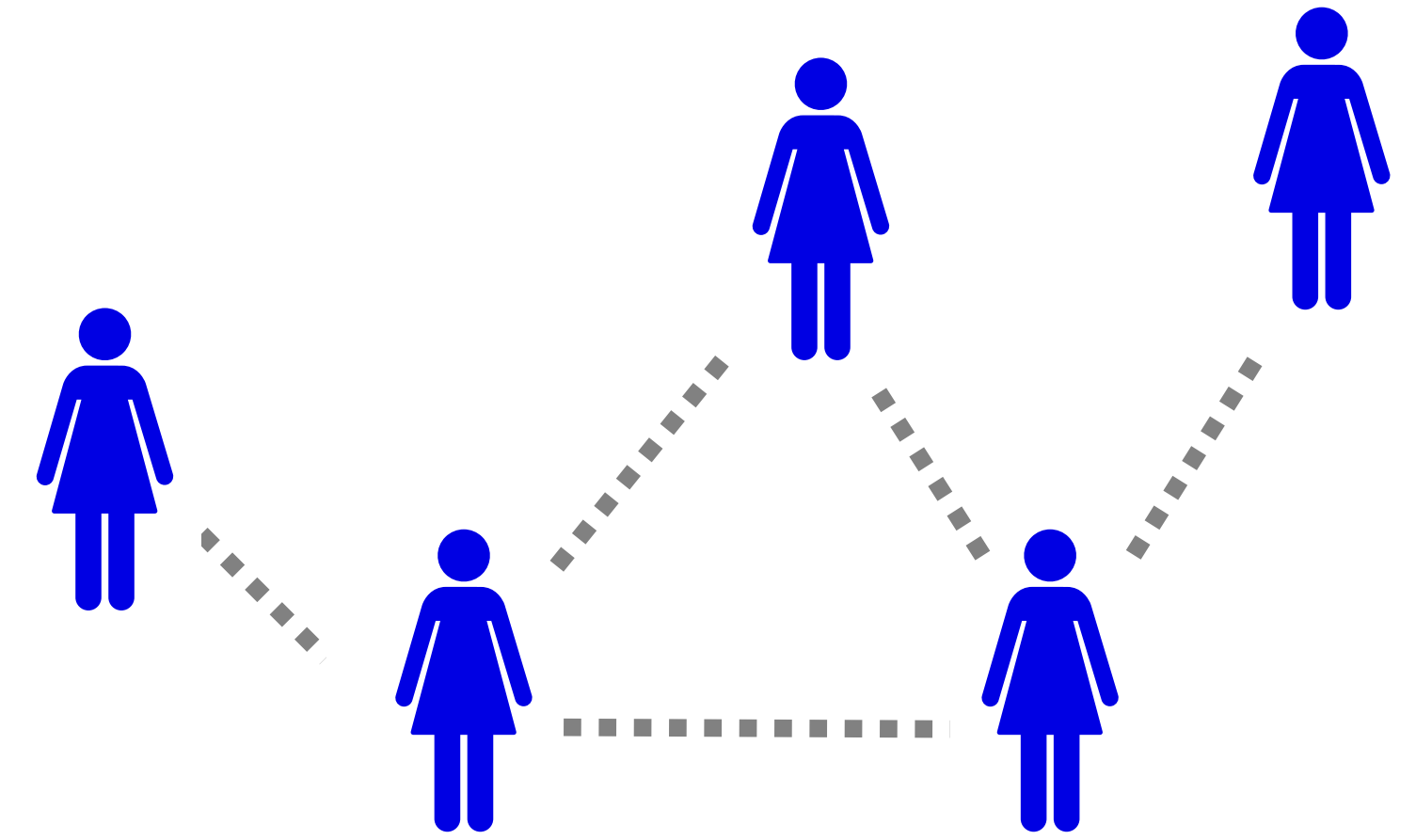
Contact network

Network properties (clustering, degree distribution) and contact dynamics.

Modelling disease progression: SIR
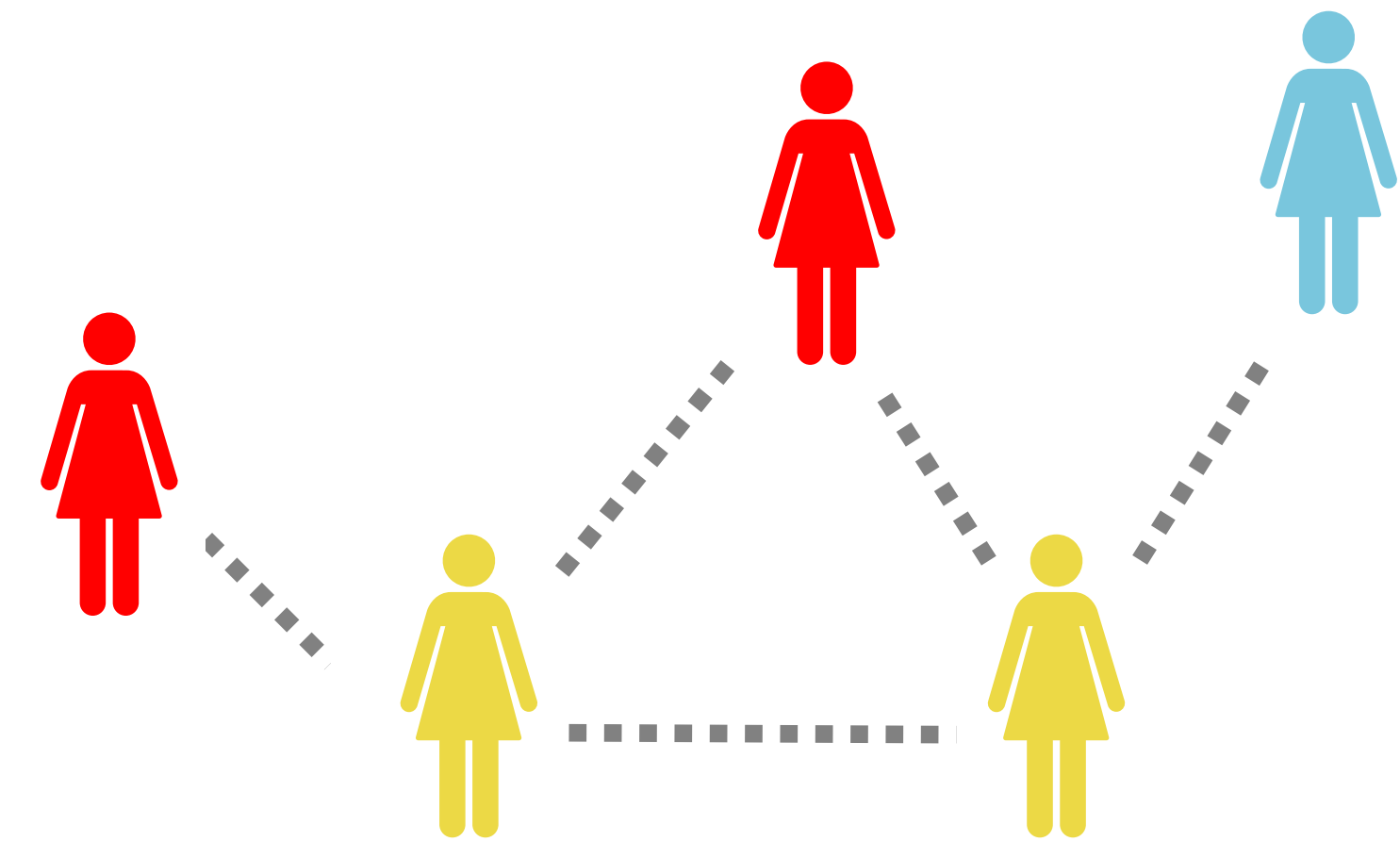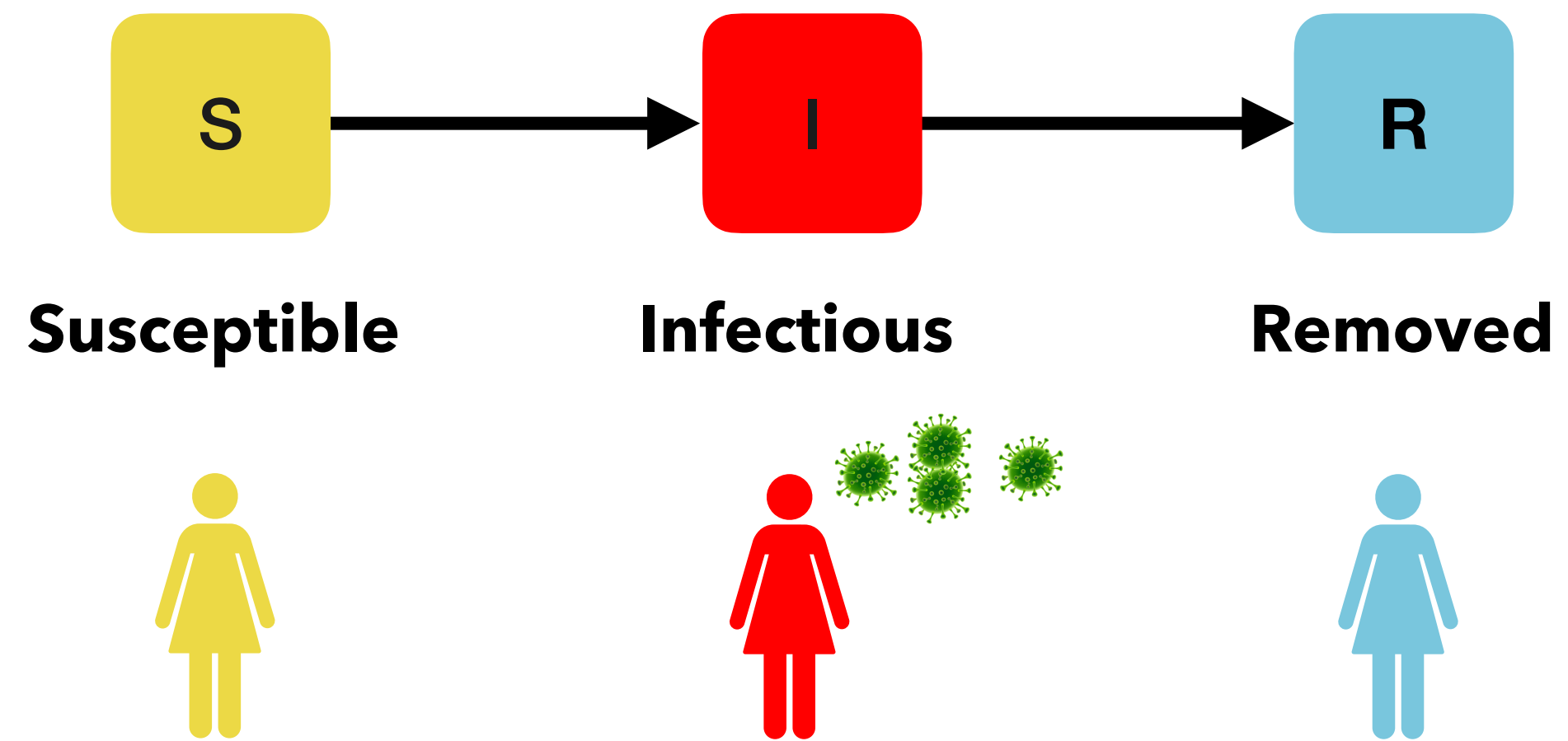
Modelling disease progression: Covid-19
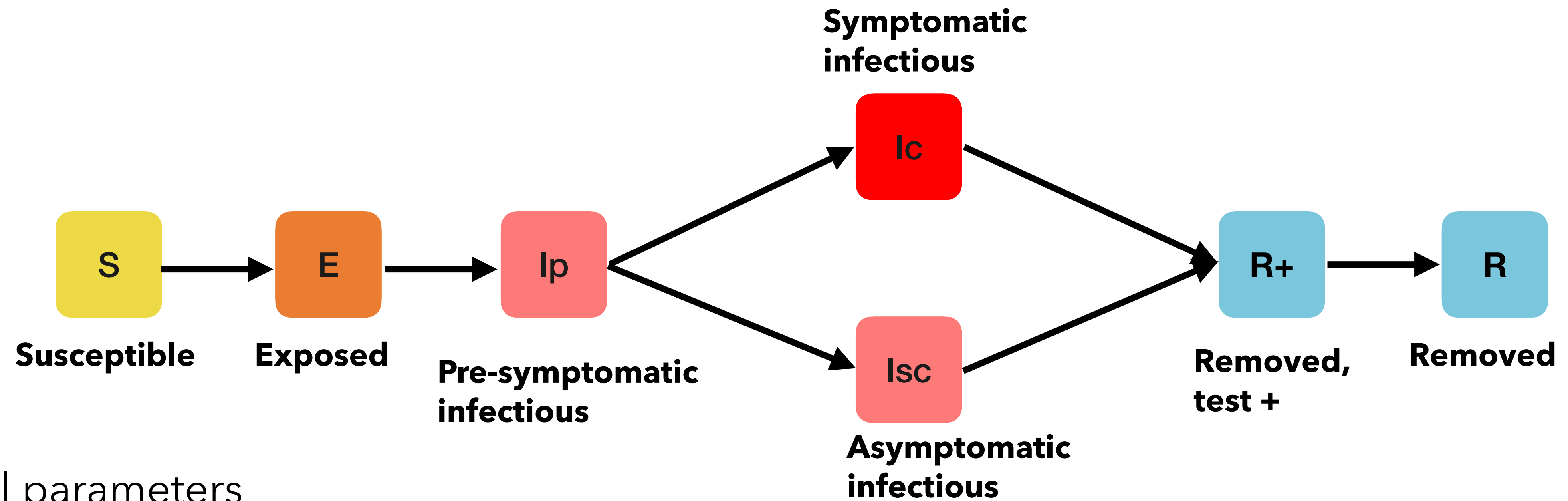
Model parameters

- determined from the literature

- drawn from distributions → heterogeneous individuals

- fitted

Data on contacts: automated detection

Face to face proximity recorded over time.

Deployed in a workplace, schools, a conference, hospital ward …

SocioPatterns collaboration
www.sociopatterns.com

Empirical contact networks

- Zoo of high-resolution human behaviours.

- Encode possible transmission routes.

- Includes temporal dynamics, contact duration & timestamps.

- Playground to investigate data needs, impact of different features.

But…

- Short collection windows.

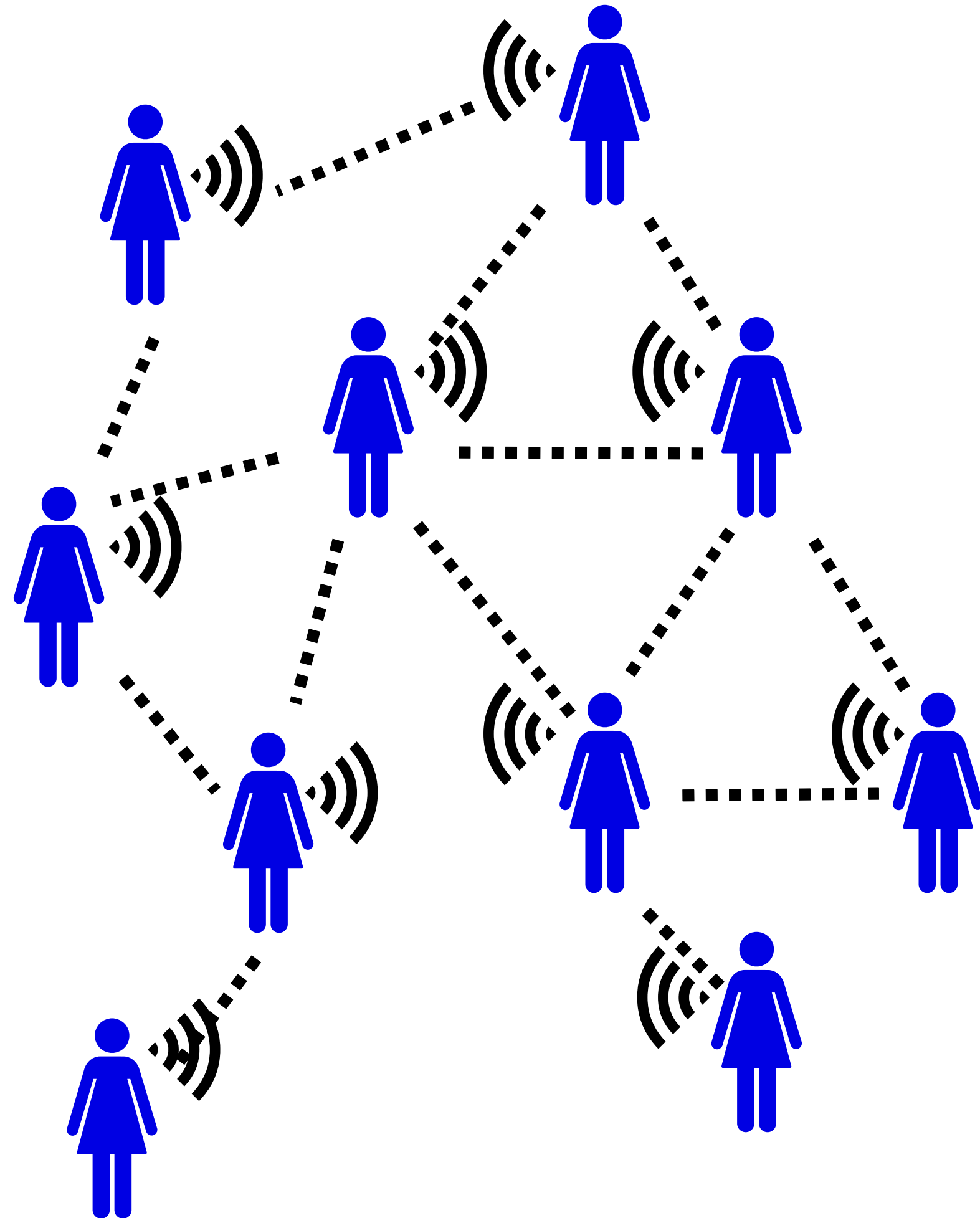- Limited to settings considered & the individuals wearing sensors.

Machen et al (2013) *BMC Infectious diseases*

Stehlé et al (2011) *BMC Medicine*

Contreras et al (2022) *J. R. Soc. Interface*

…

Leveraging on empirical contact networks

→ Toolbox to inform models with realistic contacts.

- simulate missing nodes

Genois et al (2015) *Nature Communications*

Fournet et al (2017) *Scientific Reports*

Presigny et al (2021) *Physical Review E*

- extend contacts in time

Stehlé et al (2011) *BMC Medicine*

Colosi et al (2022) *The Lancet Infectious diseases*

Longa et al (2024) *Communications Physics*

- modify context features, e.g. size extension or different timetable

Tool #1: extending in time

Temporal contact data recorded in a secondary school [1]

→

Synthetic plausible contact data over any period

→

Modelling work informed by low cost realistic input

[1] Mastrandrea et al (2015) *PLOS ONE*

Guiding questions

1. What features must be preserved to obtain "plausible" contacts?

2. What are the effects on epidemiological outputs?

3. Is there an ideal collection window?

Face to face contacts in schools

- **Class mixing**: contacts within classes and within specialties more frequent.

- **Timetable**: increased mixing during breaks and lunch.

- **Friendships**: contacts reoccur over different days: missing in existing methods

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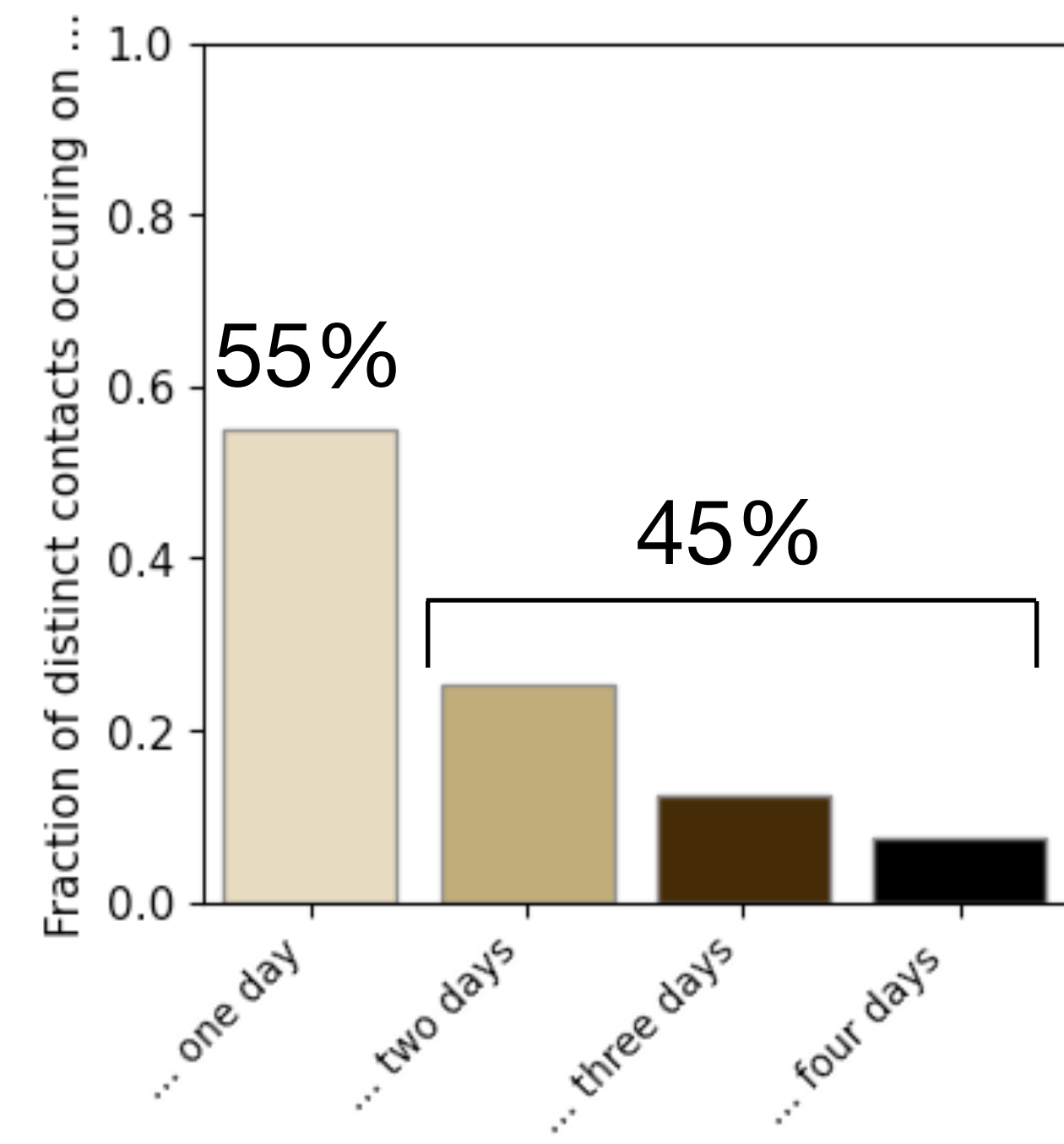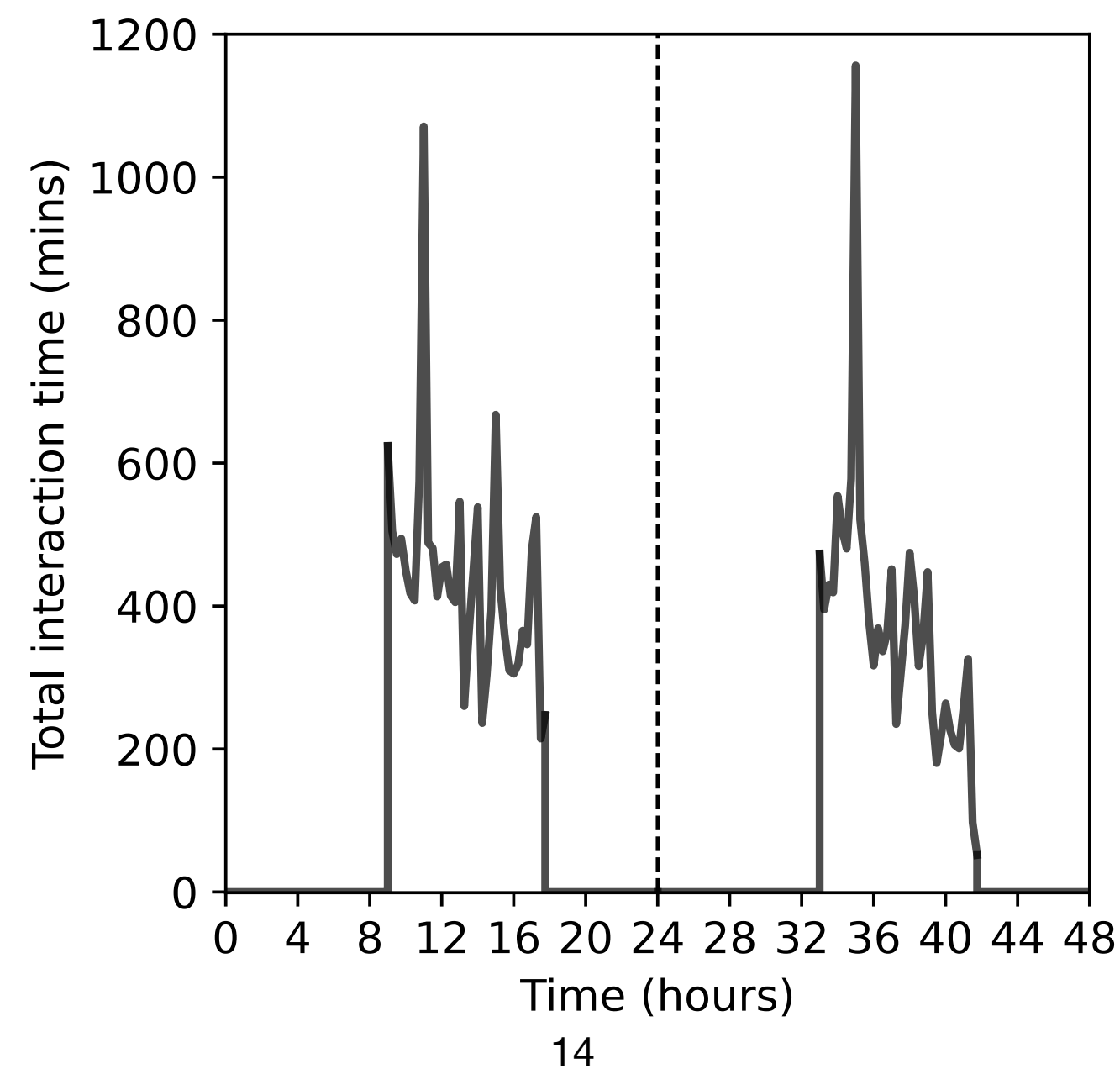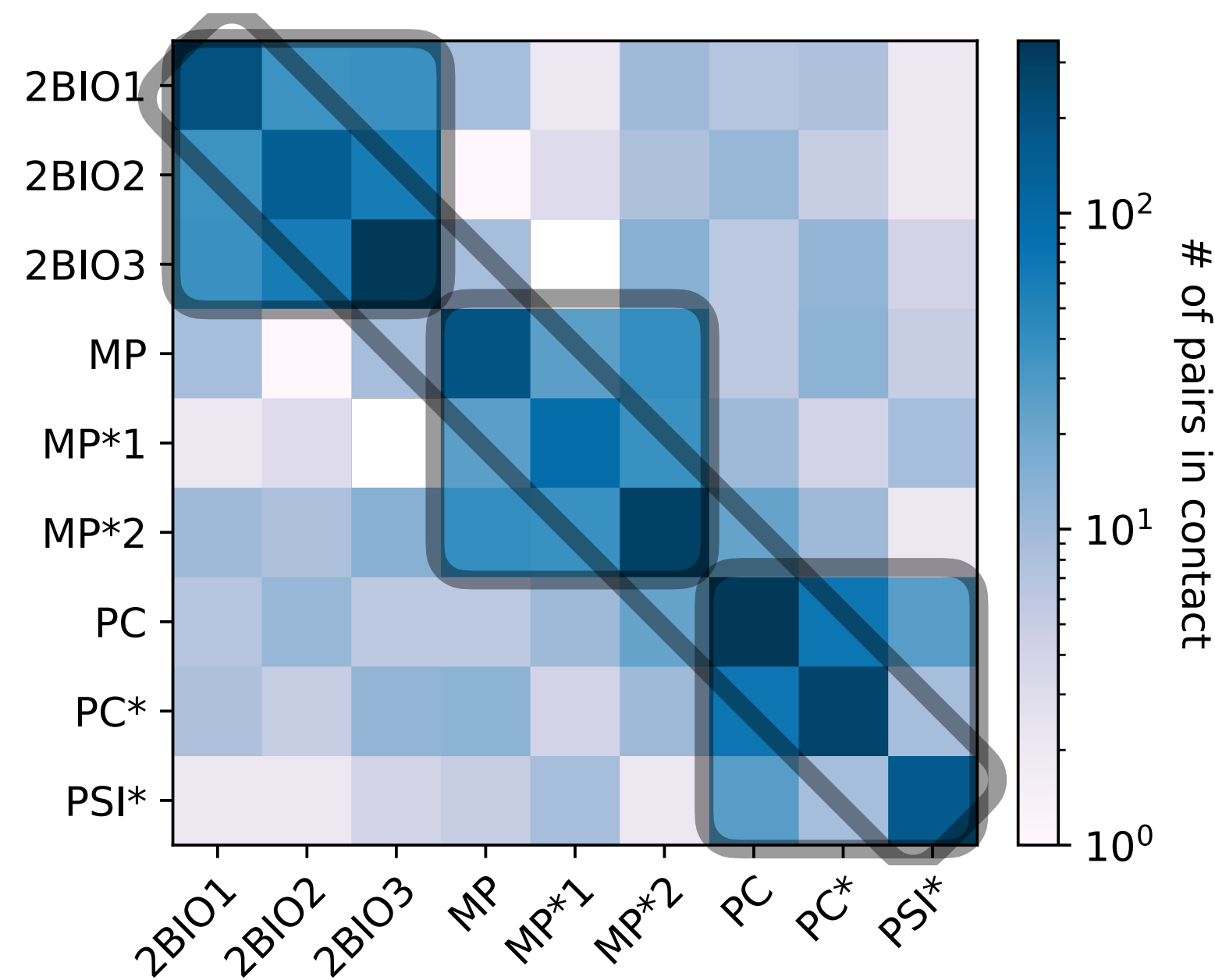
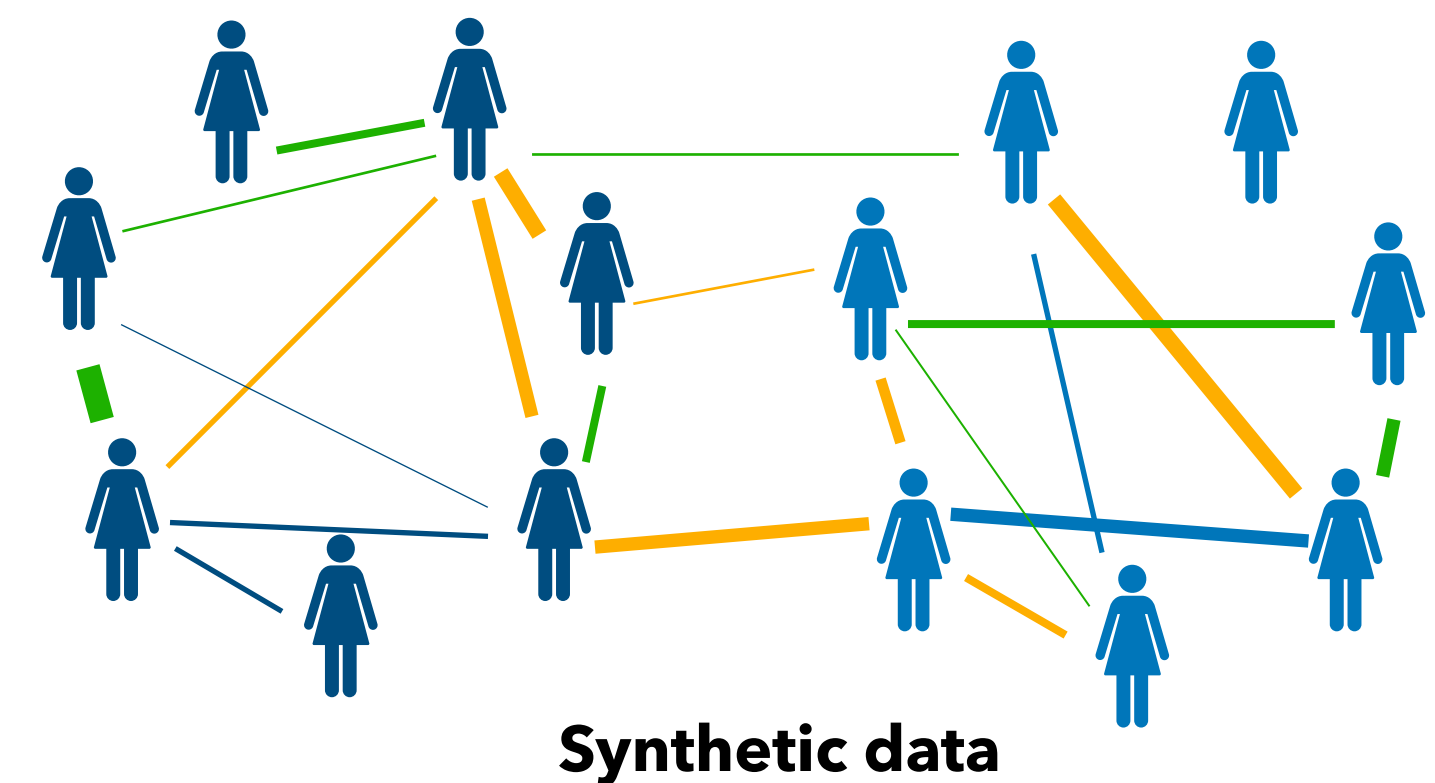# Friendship based approach

For each class and pair of classes:

- **Reccurring contacts**: fraction f → include in synthetic the contacts.

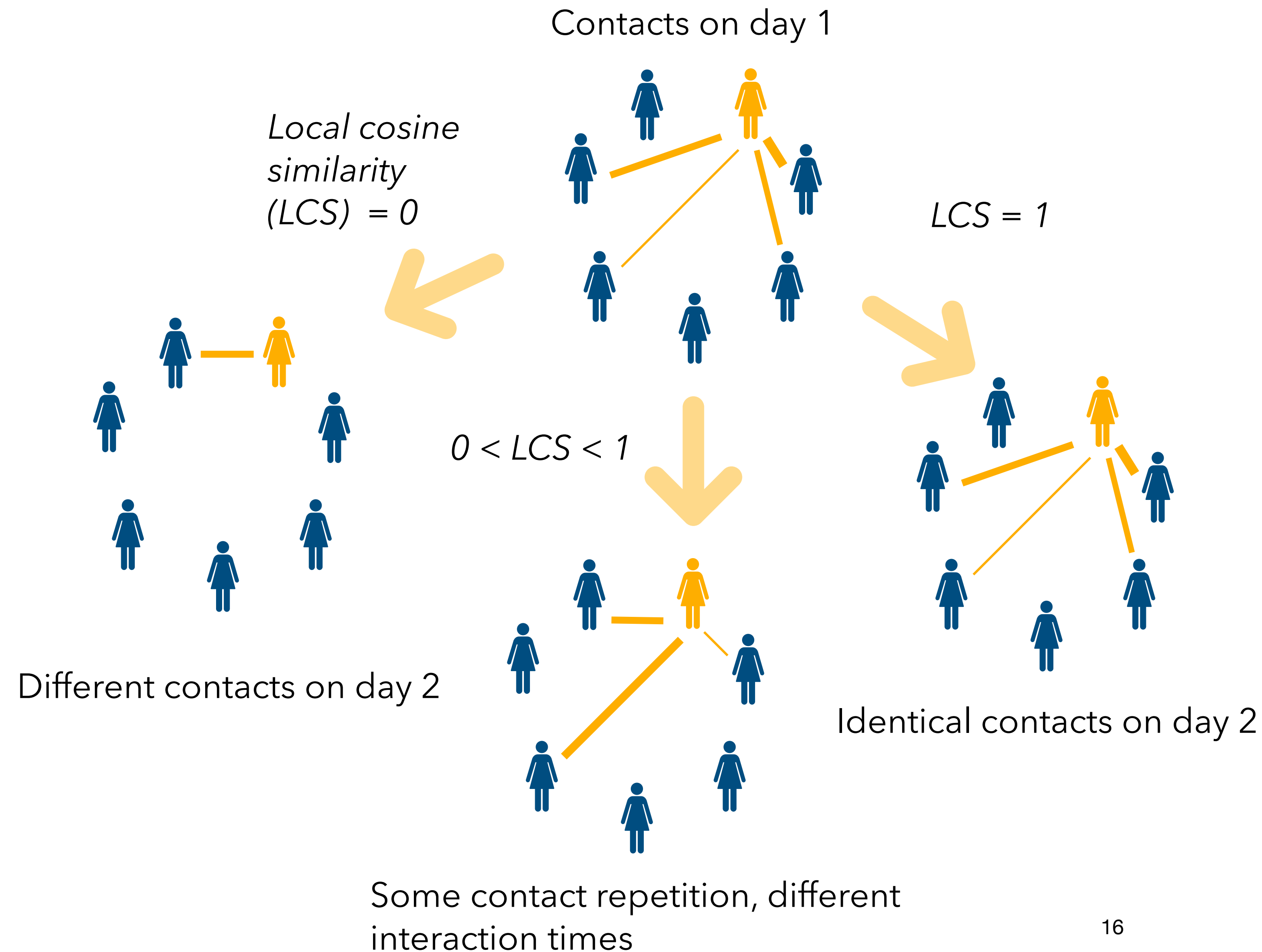- Complete synthetic contacts with additional contacts to **preserve class mixing matrix**.

Recorded data
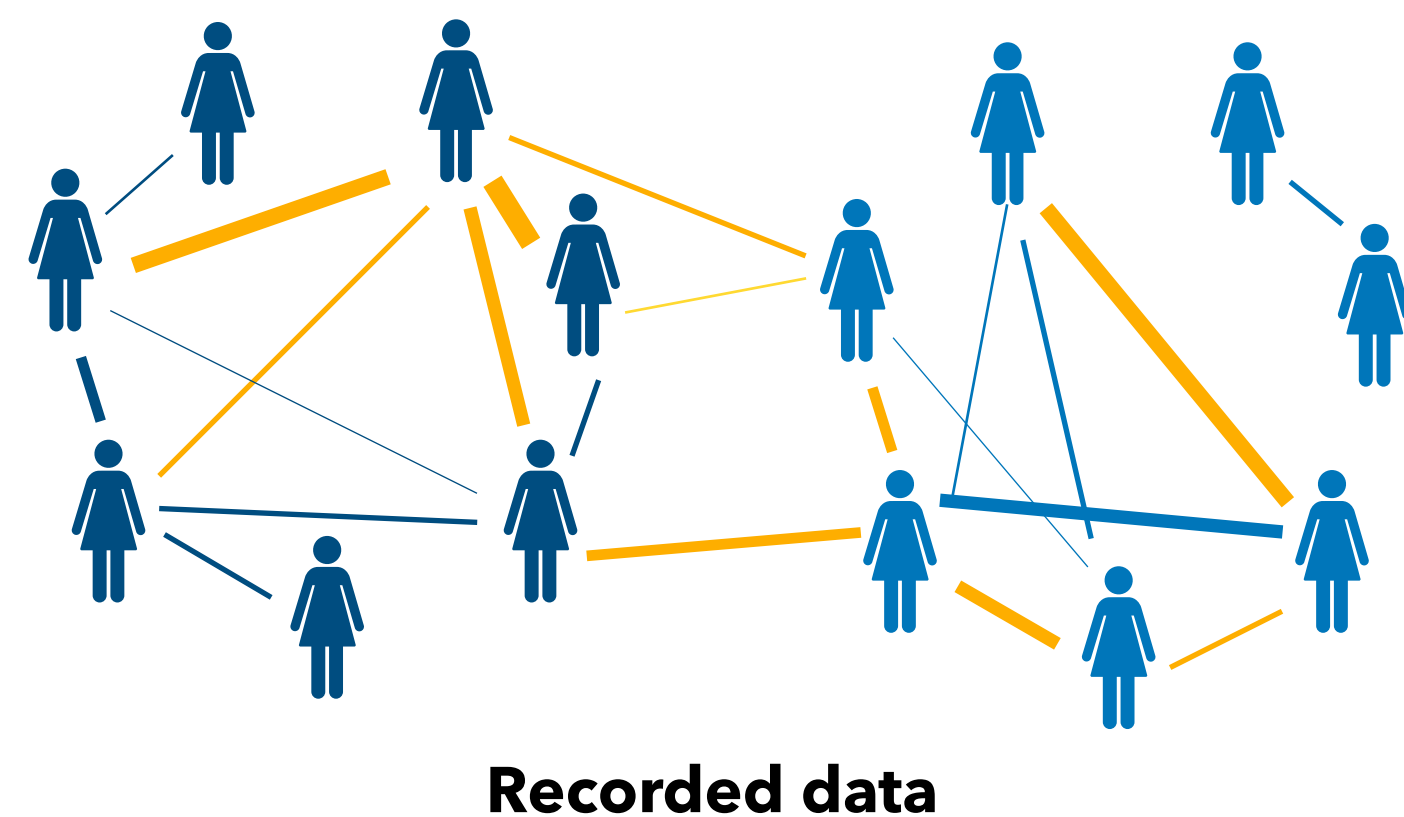
Each day of data can be copied

Synthetic data

→ **Pick** f **to reproduce observed similarities in day-to-day contacts**

Day to day correlations

Contacts on day 1

Local cosine similarity (LCS) = 0

LCS = 1

0 < LCS < 1

Different contacts on day 2

Identical contacts on day 2

Some contact repetition, different interaction times

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Individuals with different contacts

Individuals with identical contacts

Friendship approach
Recorded data
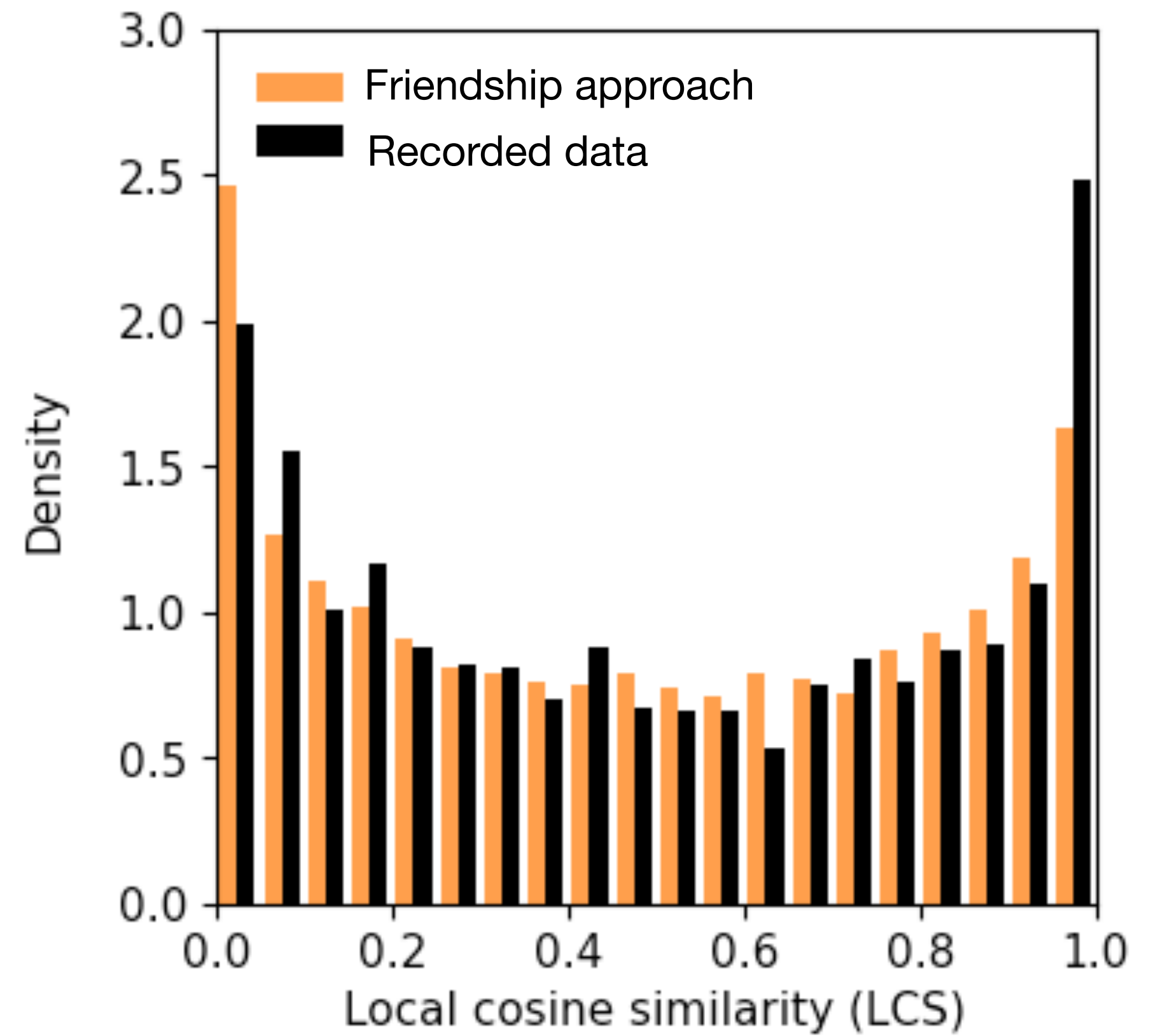
Preserved distribution of similarities

Calmon et al. (2024), in preparation

Class mixing and timetable

- Class mixing matrix preserved.
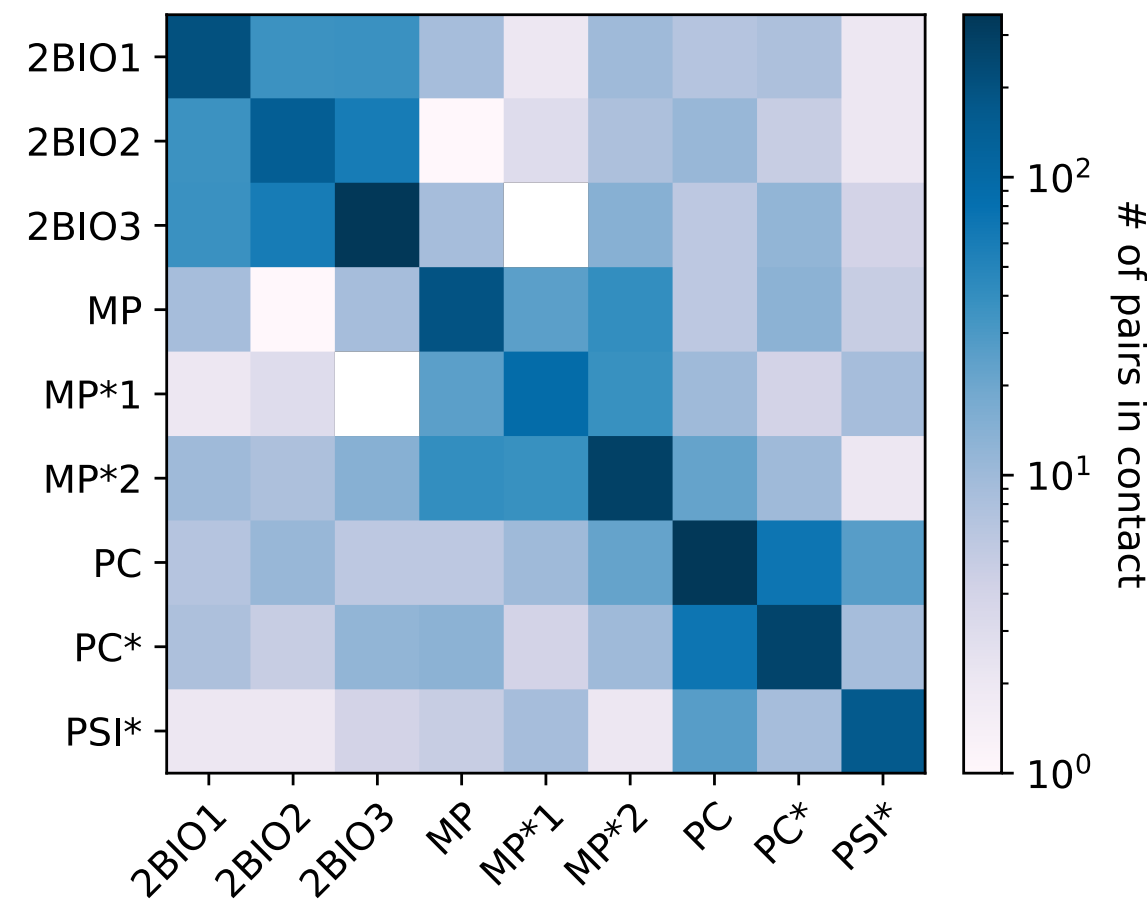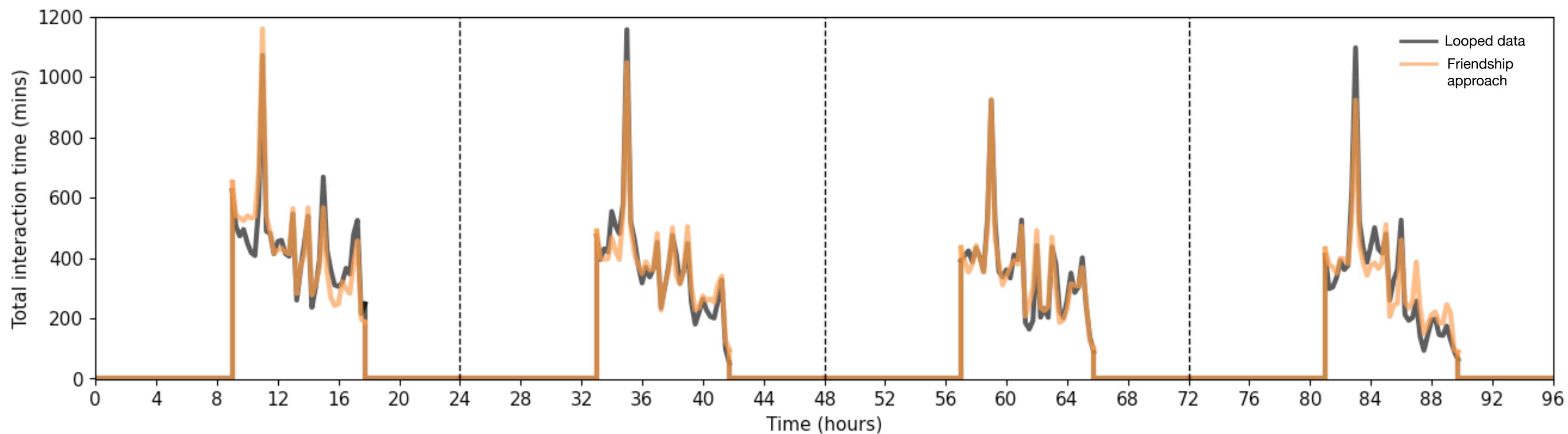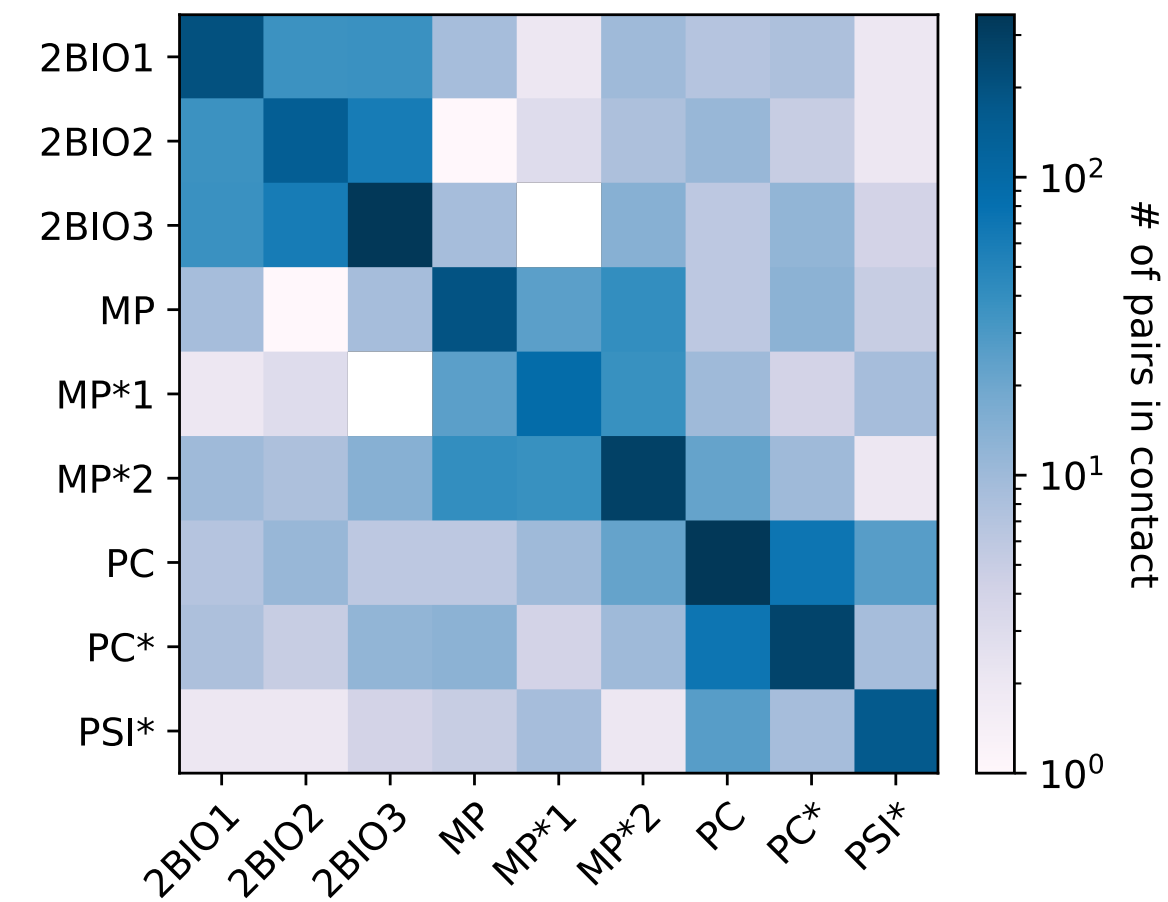
- Similar timetable induced.

Recorded data

Friendship approach

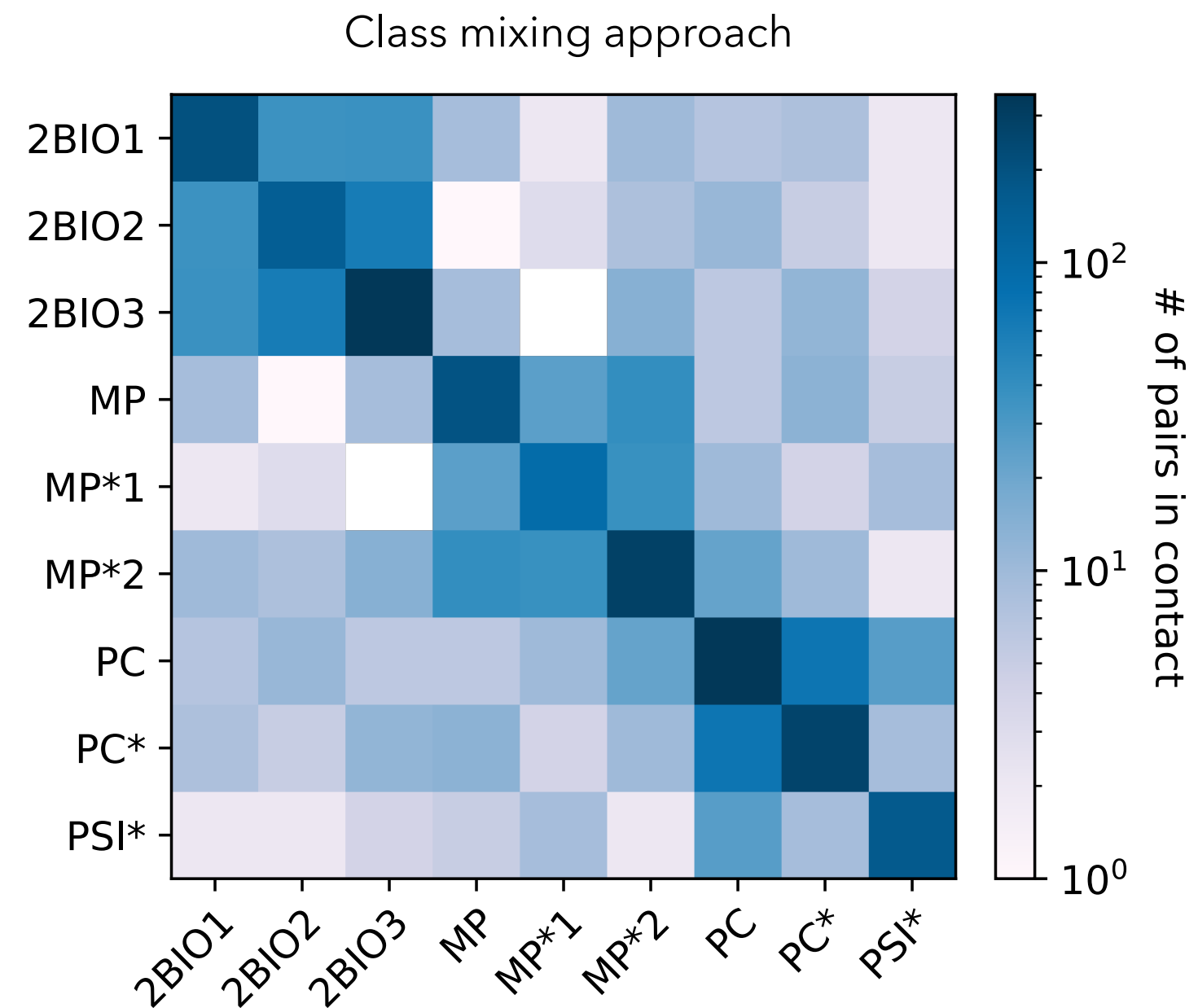Calmon et al (2024) *in preparation*

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Class mixing approach

Recorded data

Class mixing approach
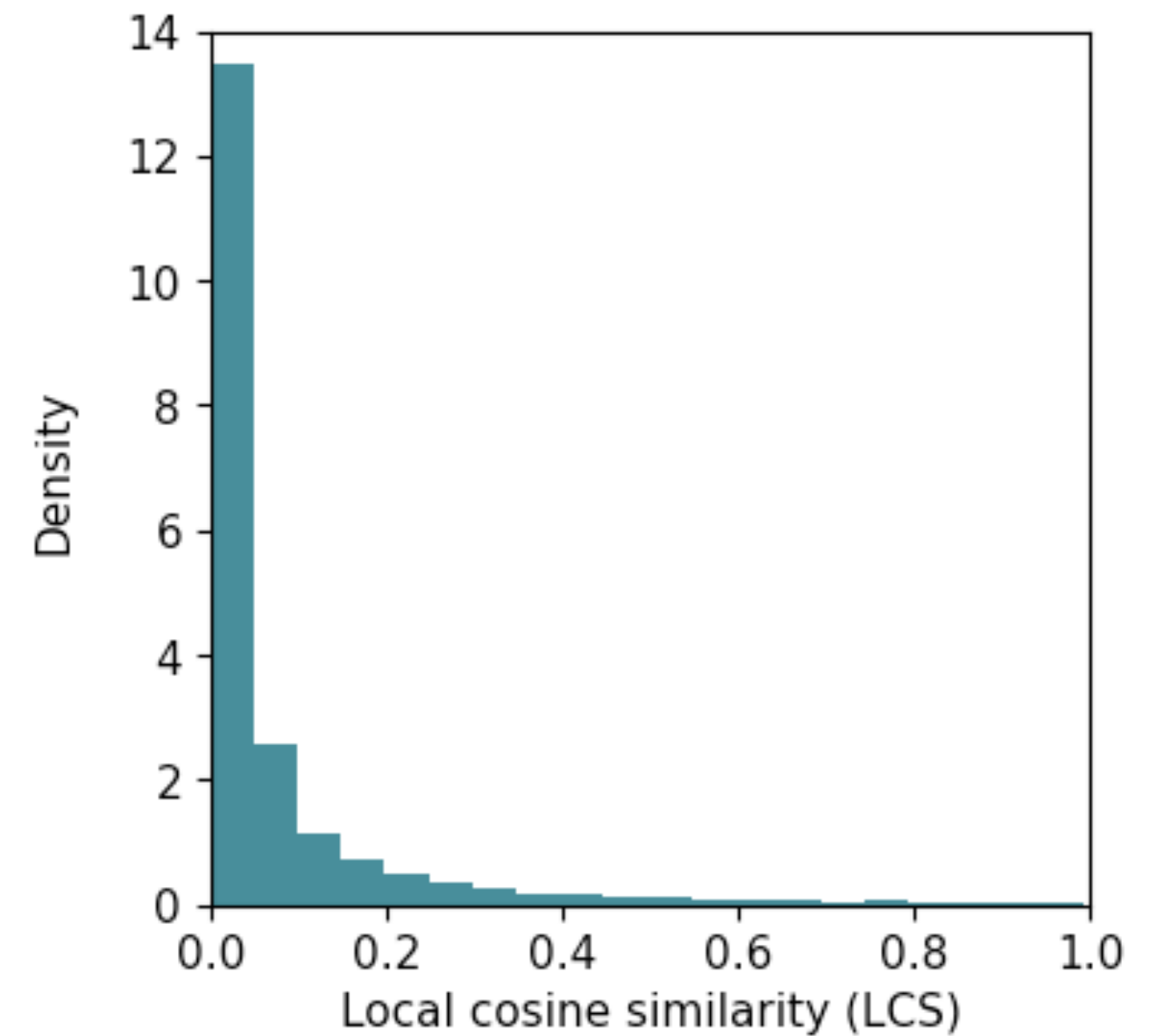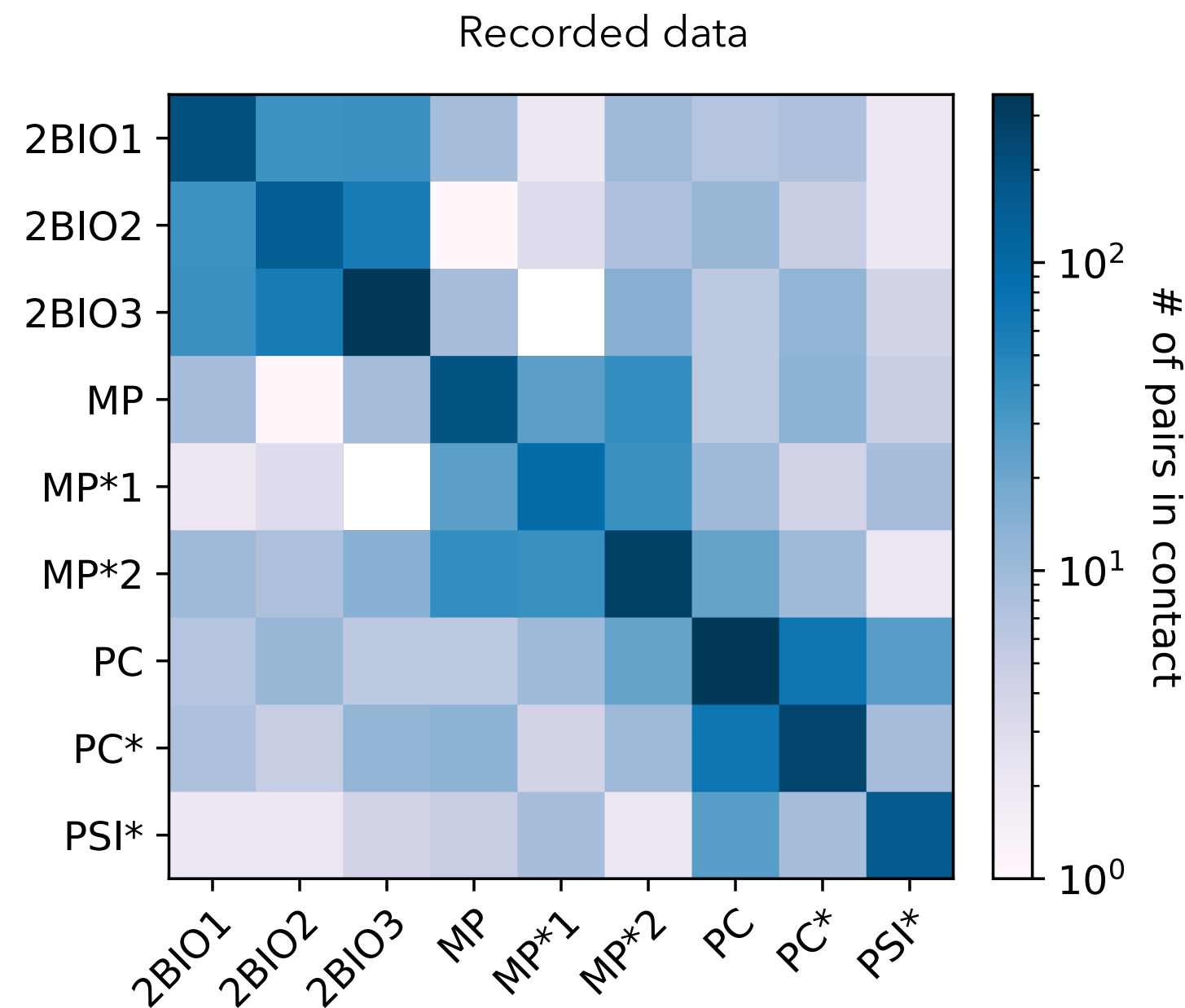
Preserves the mixing **patterns between classes** and the activity timeline (not shown).

Friendships absent.

Calmon et al. (2024) *in preparation*

Modelling Covid-19 on synthetic contacts

Symptomatic infectious

Ic

S	E	Ip

Susceptible · **Exposed**

Pre-symptomatic infectious

Isc

Asymptomatic infectious

R+ **R**

Removed, test + · **Removed**
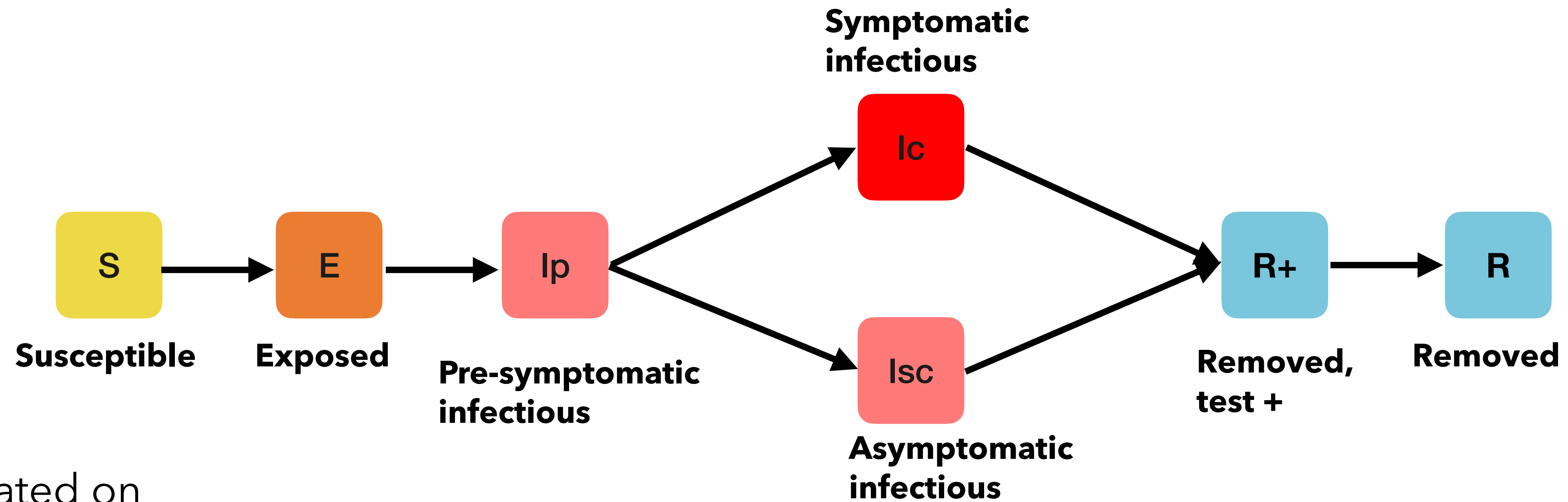
Simulated on

- **friendship based** contacts using 2, 3, 4 days of data

- **class mixing** based 1, 2, 3, 4 days of data

- **looping** 1, 2, 3, 4 days of data

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Colosi et al (2022) *The Lancet Infectious Diseases*

Outbreak size: total # of cases
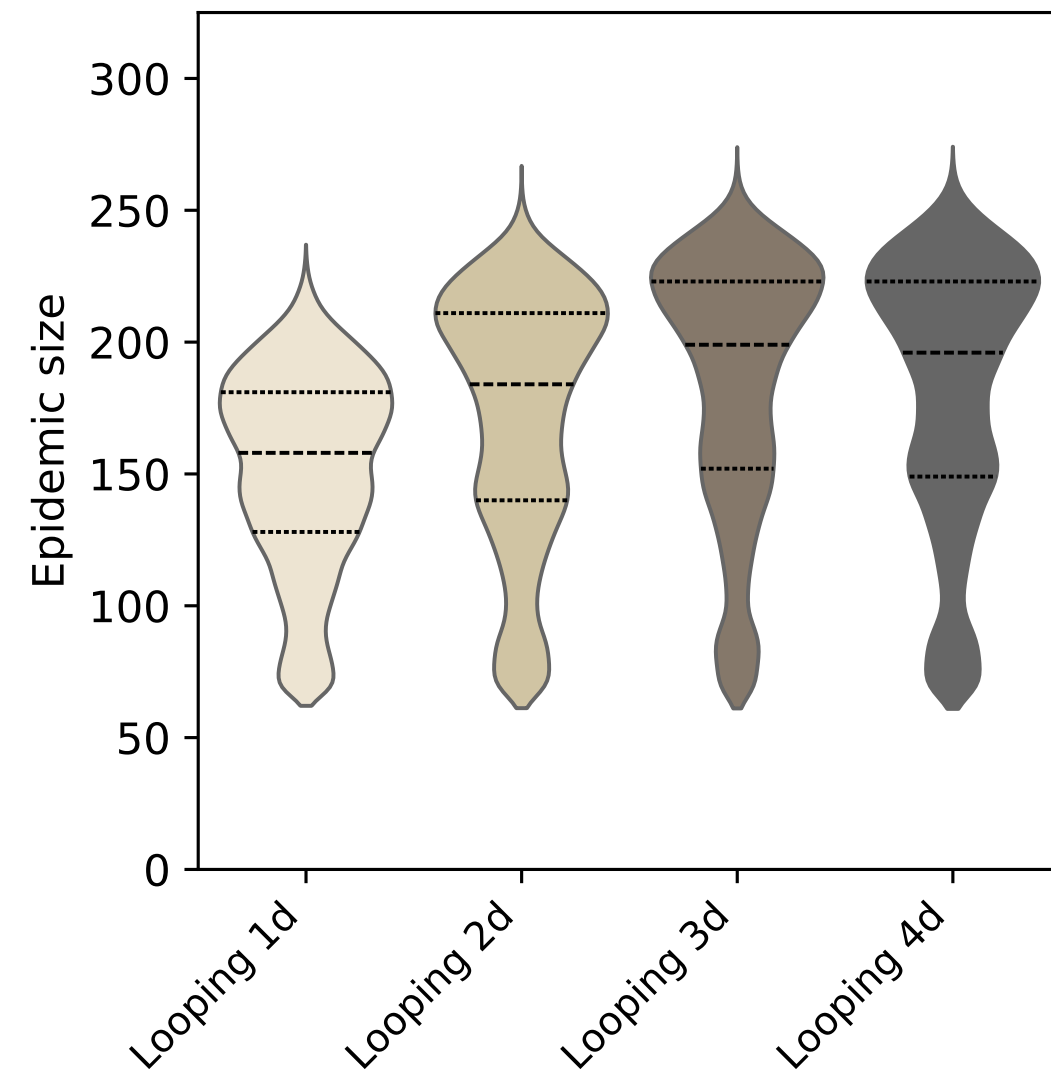
Calmon et al (2024) *in preparation*

Looping the data → low probability of small outbreaks.
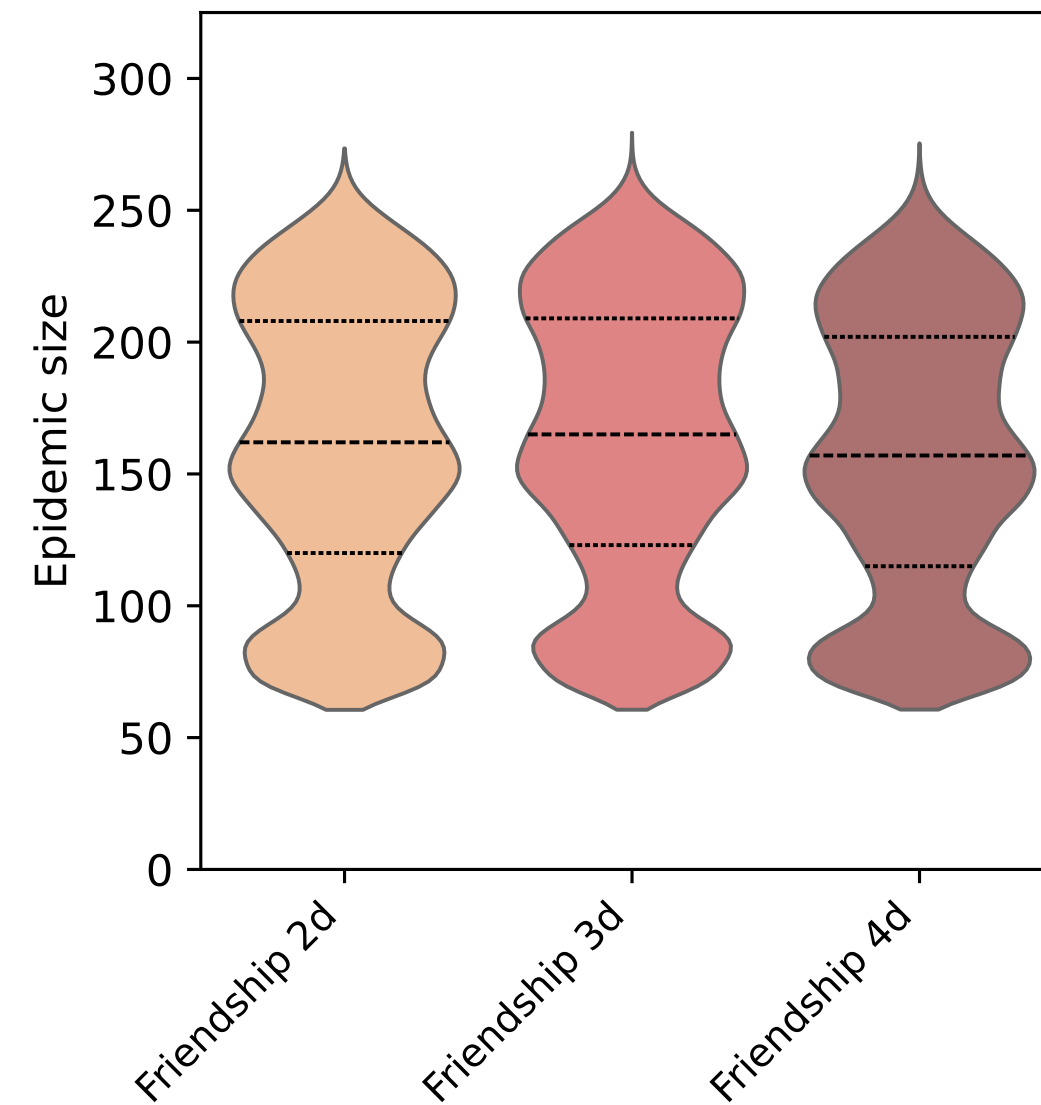
Synthetic contacts → promotes heterogeneity in outbreak sizes.

Friendship based approach → promotes larger outbreaks.
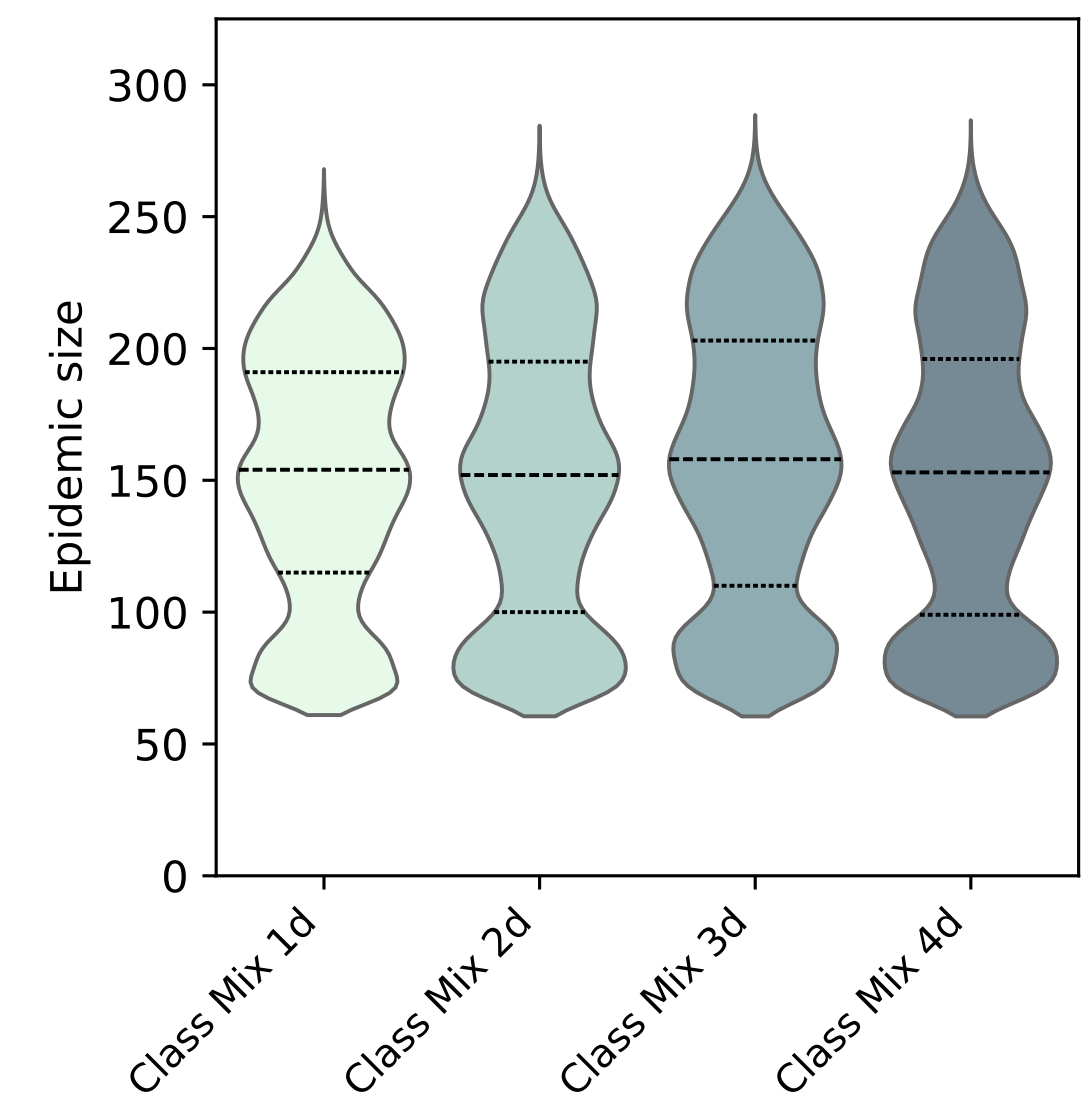
Infection pathways

- For each seeded case, and contact extension mechanism: **aggregated spanning tree.**

- Edges weighted with **probability of occurrence**.

- Pairs of trees/networks can be compared.

- Encode the pathways **between students** or from **class to class**.

Representative aggregated infection tree (maximum spanning tree) [1]

Between classes

[1] Piontti et al (2014) *Network Science*

Comparing transmission trees

- Friendship based trees and trees from looped data are similar.

- Trees predicted by the class mixing approach are strongly affected by the missing friendships.

Comparing transmission trees

Between classes

Global cosine similarity to Friendship 2d

Calmon et al (2024) *in preparation*

- **High similarity** between Friendship based trees and looping & class mixing based trees.

- Robust tree predictions from class mixing based approach to synthetic contacts.

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Extension in time

Friendship & class mixing approaches extend empirical contact data for different purposes.

1. **Epidemic sizes** affected by stochasticity in contacts & friendships preservation.

2. **Friendship** based mixing is key to represent **student transmission trees**.

3. Class mixing predicts accurate disease **progression between classes**.

Retrospective study: modelling pooled tests

Repeat test after one week

1 **Registration to the testing programme**

School class

2 **Saliva sample taken at home/at school**

after 1 week

3 **Class is pooled at the lab**

4 **PCR analysis at the lab**

5 **Test result available to the test centre**

6-10 h

Negative test result to the school

Negative pool

Positive pool

6 **Individual test at the test centre**

No measures

Negative

Test result to the student

Approx 12-18 hours

Positive test result to the school

Isolation

Positive

Translated from https://www.nau.ch/news/schweiz/coronavirus-eltern-skeptisch-bei-massentests-an-schulen-65879525
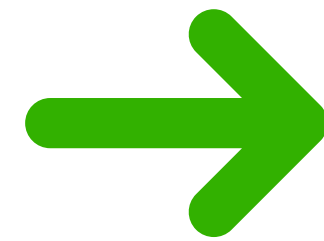
Retrospective study: modelling pooled tests

Build a model to quantify …

- Transmissibility of the virus at school

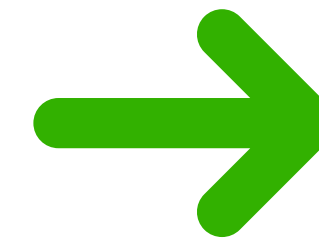- # of averted cases

- Impact on school days lost

Colosi et al (2024) *in preparation*

Tool #2: changing features

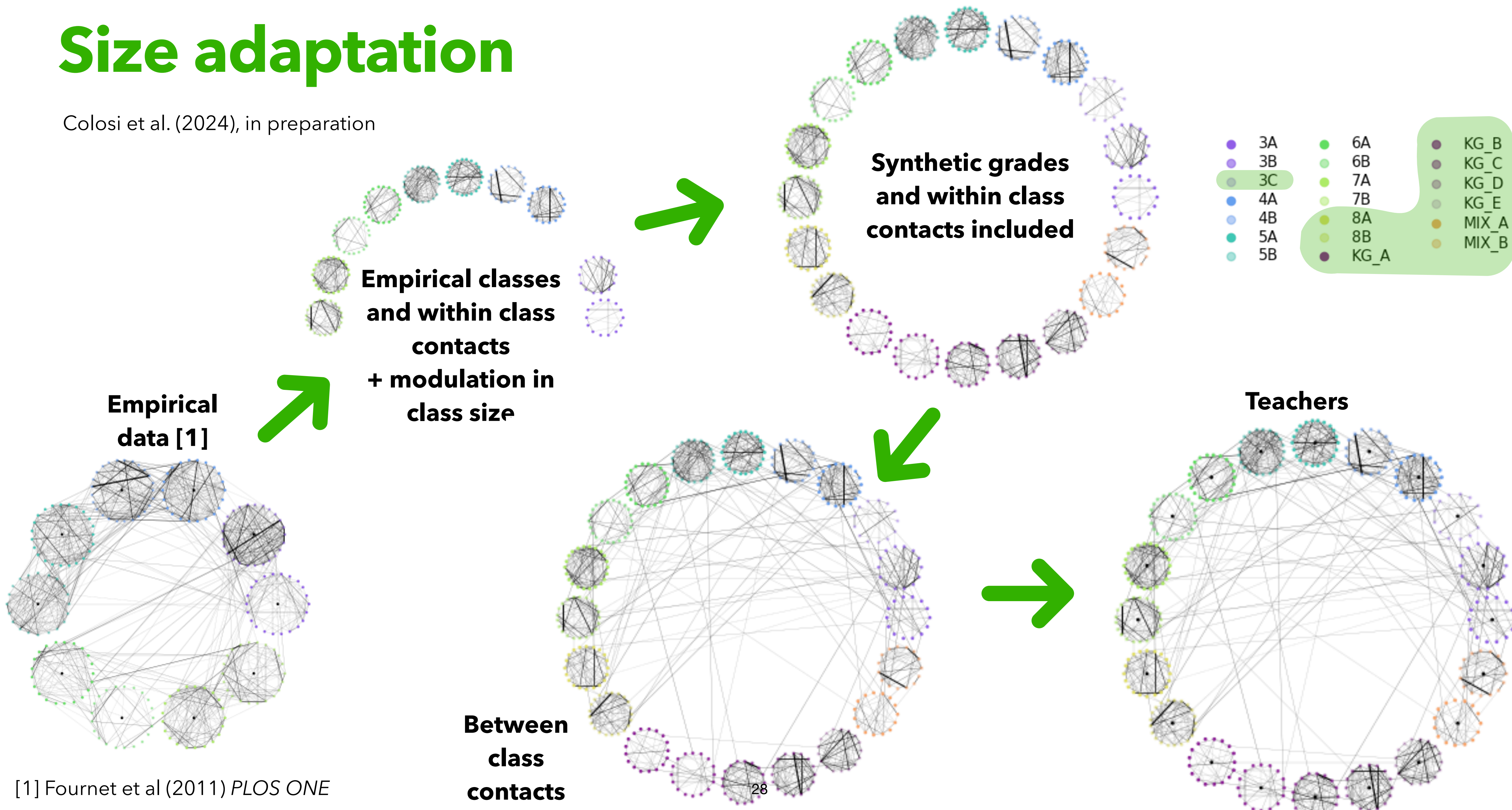Characteristics of the stereotypical school.
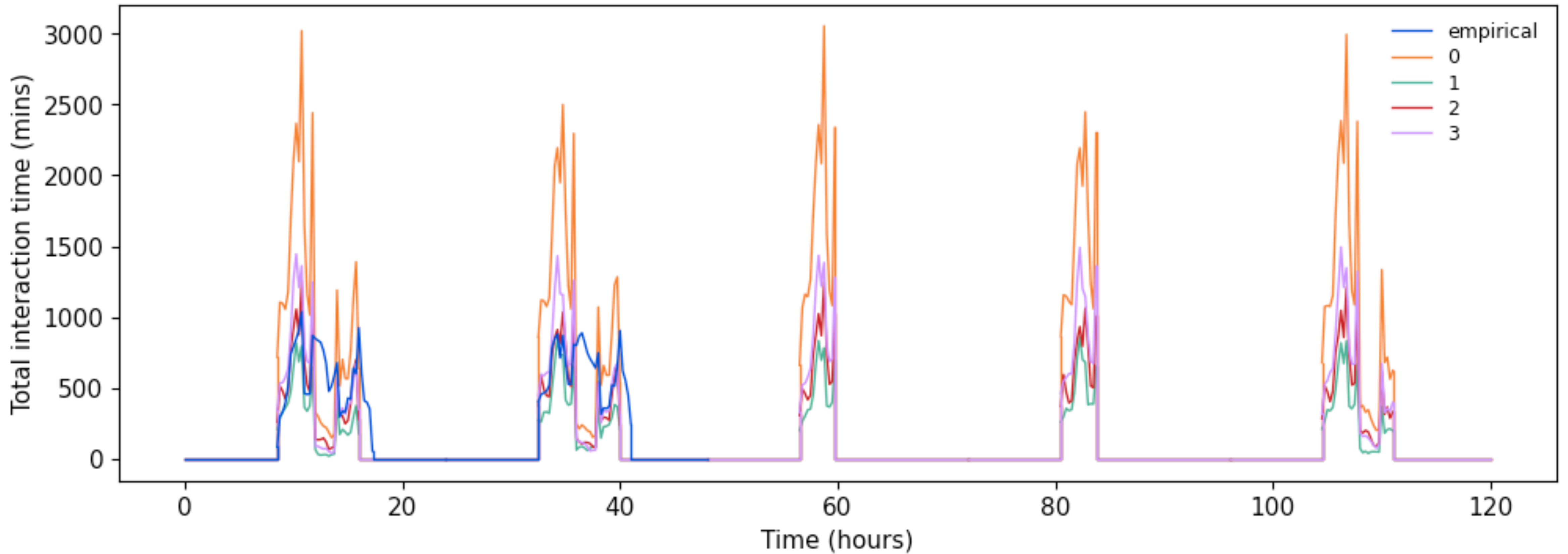
→

Size modulation of the empirical contacts.

→

Timetable change + extension in time.

Size adaptation

Colosi et al. (2024), in preparation

Synthetic grades and within class contacts included

Empirical classes and within class contacts + modulation in class size

Empirical data [1]

Between class contacts

Teachers

3A	6A
3B	6B
3C	7A
4A	7B
4B	8A
5A	8B
5B	KG_A

KG_B
KG_C
KG_D
KG_E
MIX_A
MIX_B

[1] Fournet et al (2011) *PLOS ONE*

Timetable adaptation: one week

Colosi et al. (2024), in preparation

Modelling the pooled strategy

- Modulated and extended contacts → model of the pooling strategy.

- Data cleaning.

- Fit and calibrate the model.

- Design counterfactual scenarios.

- Comparison of different strategies to evaluate pooled tests.

Moving forward

- Contacts in schools can be extended and modulated.

- Organisation in classes and grades + timetable.

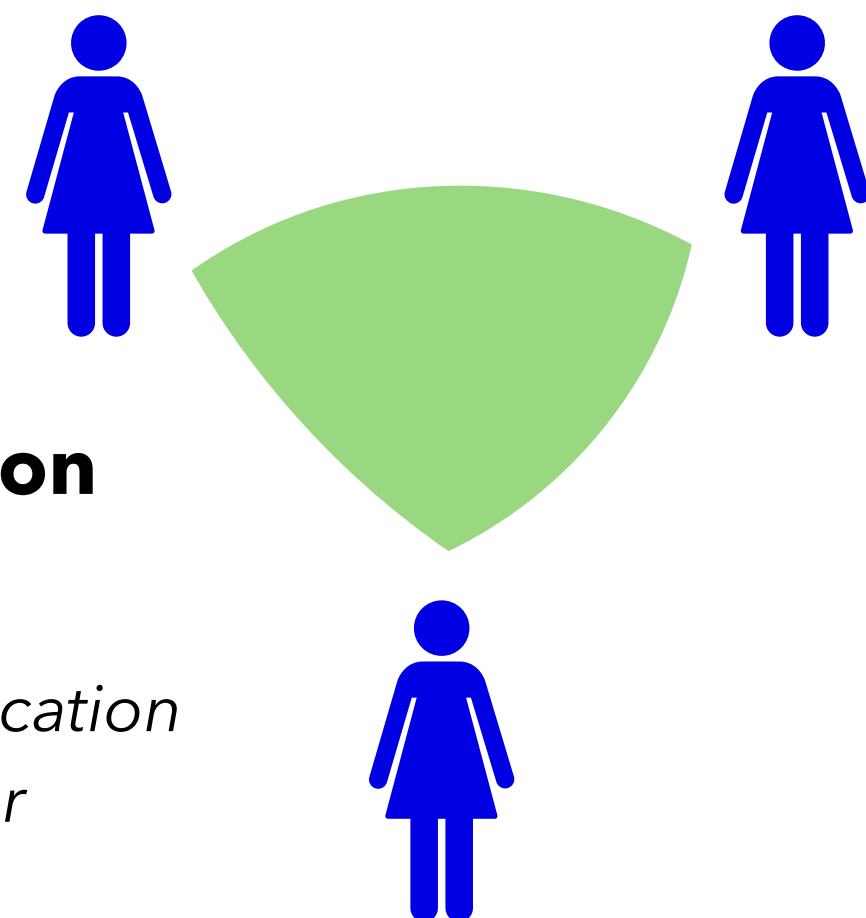- Temporal correlations extended → impact on simulated transmission chains.

- What about other contexts ?

- What about impact of illness on contacts & behaviours ?

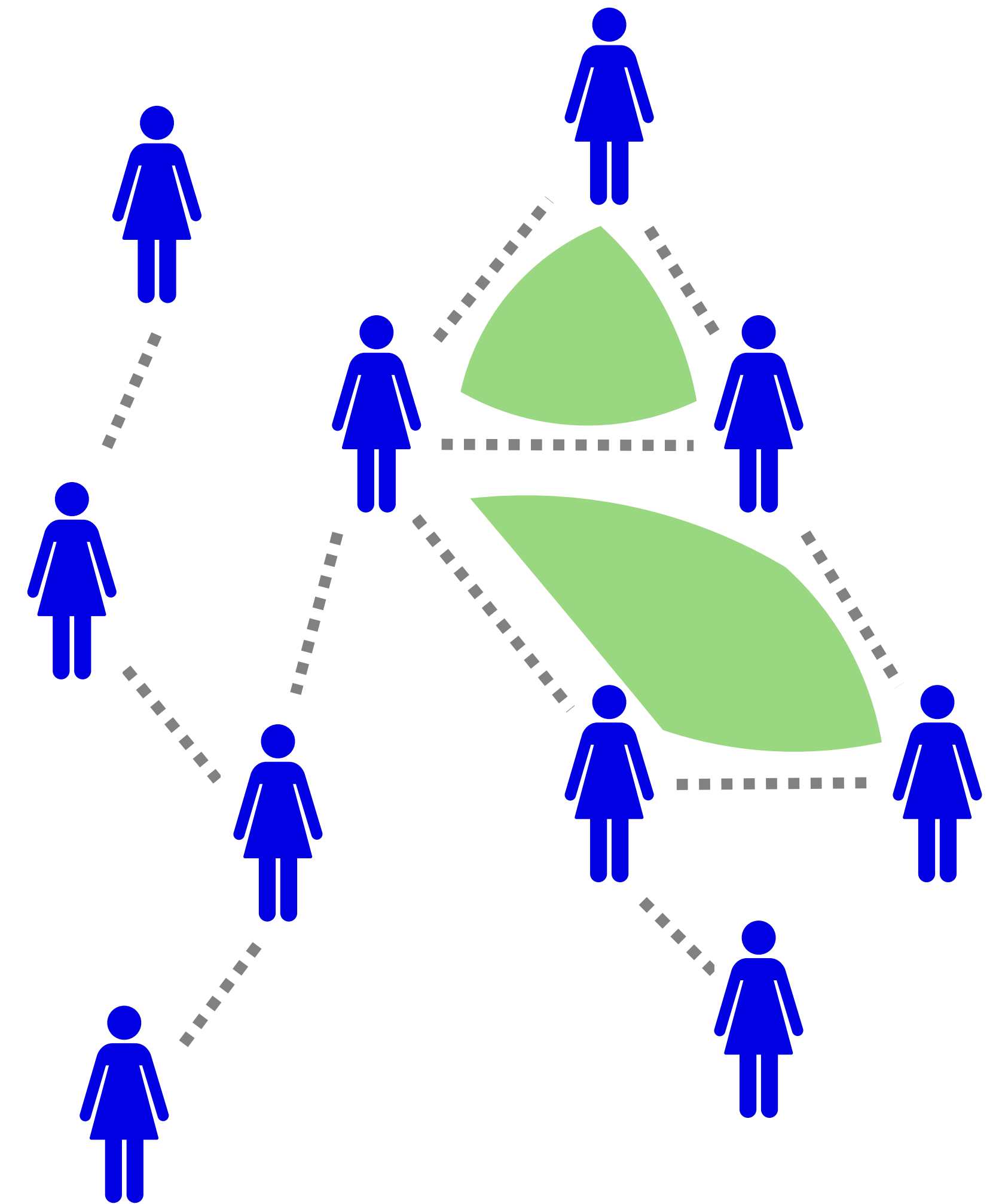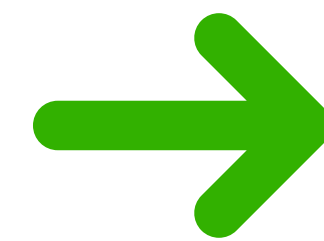- What about other modes of transmissions ?

Contagion

Simple contagion
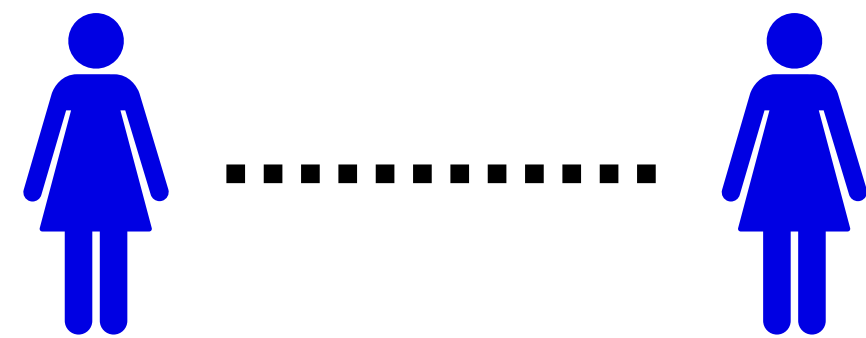
Complex & simplicial contagion

Mønsted et al (2007) *PLOS ONE*
Iacopini et al (2019) *Nature Communication*
Ferraz de Arruda et al (2022) *Springer*
…

…

Joint coupled spreading on (higher-order) networks

Wang et al (2022) *Chaos*
Lucas et al (2023) *Physical Review Research*
….

Thank you

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